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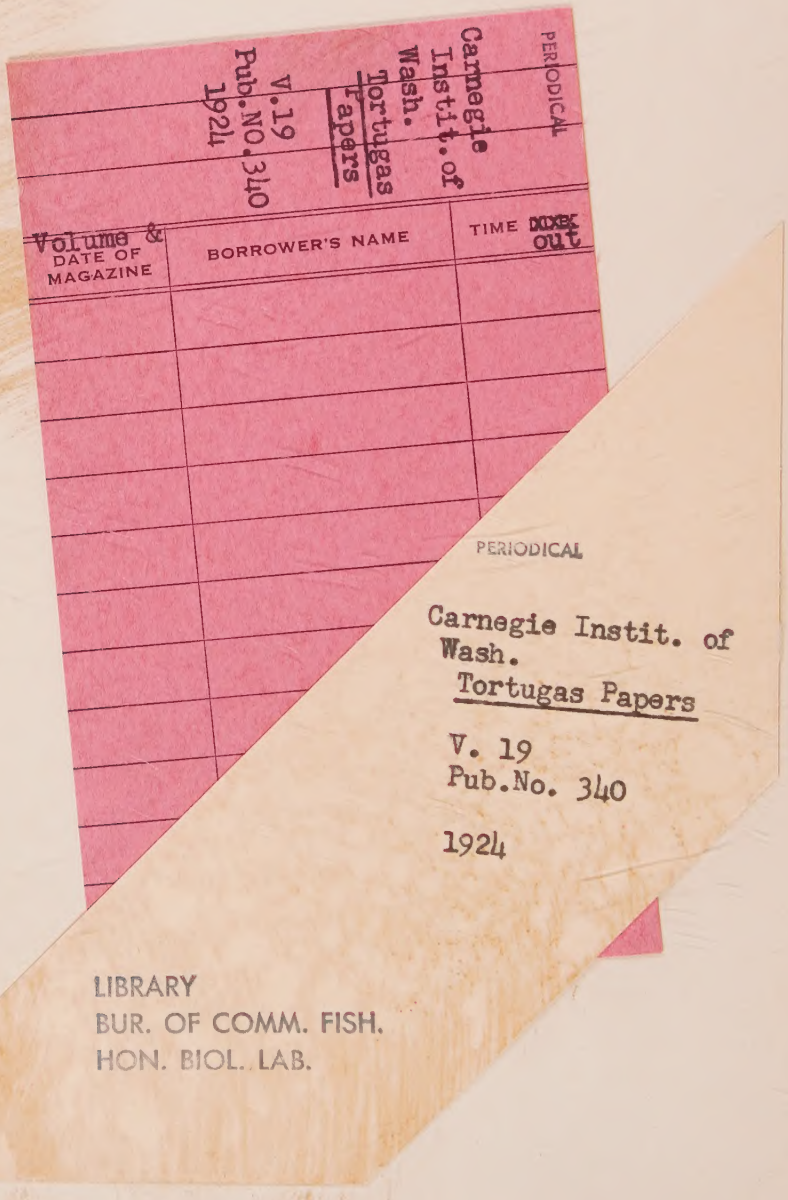

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Alfred G. Mayor

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PAPERS FROM THE DEPARTMENT OF MARINE BIOLOGY
OF THE CARNEGIE INSTITUTION OF WASHINGTON

VOLUME XIX

A MEMORIAL TO

ALFRED GOLDSBOROUGH MAYOR

SOME POSTHUMOUS PAPERS OF A. G. MAYOR

RELATING TO

HIS WORK AT TUTUILA ISLAND AND ADJACENT REGIONS

TOGETHER WITH REPORTS OF

R. A. DALY, R. T. CHAMBERLIN, AND C. B. LIPMAN
ON THEIR WORK IN THE SAME CONNECTION

PUBLISHED BY THE CARNEGIE INSTITUTION OF WASHINGTON
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A.—One of the last photographs of Dr. Mayor, showing him at work on a Samoan coral reef.

B.—The *Darwin* off the Tortugas Laboratory. Ready for subsea explorations.

PREFACE.

This volume contains reports on some of the investigations conducted by an expedition of the Department of Marine Biology of the Carnegie Institution of Washington to the island of Tutuila and adjacent regions. The time covered was from March 4 to April 18, 1917; June 1 to August 5, 1918; July 21 to September 17, 1919; and April 2 to June 28, 1920. A visit to Fiji extended from April 6 to May 14, 1920.

Associated with the Director were Professors L. R. Cary, 1917, 1918, and 1920; R. A. Daly, 1919; and R. T. Chamberlin, C. B. Lipman, W. H. Longley, F. A. Potts, W. A. Setchell, and A. L. Treadwell in 1920. Mr. John W. Mills, chief engineer of the Tortugas Laboratory, accompanied us upon all of these visits to Samoa. Professor Cary studied the Alcyonaria with a view to determining their rôle as reef-builders, four borings being made through the fringing reef in Pago Pago Harbor to enable him to gather material for this study. Professor Chamberlin studied the geologic history of the reefs and the relation between them and the shore-line, and the volcanic substratum upon which they have been built up; Professor Daly made a lithological reconnaissance of the island in collecting the volcanic rocks for petrographic study; Professor Lipman made cultures of the marine bacteria of Pago Pago Harbor and also of the pure ocean-water in order to determine what rôle, if any, they may play in precipitating calcium carbonate, his special problem being to ascertain why calcium carbonate is precipitated in such abundance in the tropical Atlantic, but not in the tropical Pacific. Professor Longley made use of a diving-hood and under-water camera to study the coloration of Samoan fishes in relation to their habits. Frank A. Potts, esq., M. A., studied the growth-rate of marine invertebrates other than corals. Professor Setchell[1] devoted himself to the lithothamnium and marine algæ, and also made a collection of land plants, obtaining a list of their native names, uses, and traditions associated with them. Professor Treadwell collected marine annelids, paying special attention to the Eunicidæ.

The Director studied the growth-rate, ecology, and physiology of the reef corals, and the effects of rain and stream water and degrading agencies upon the reefs. Soundings were made to determine the submarine slopes of the seaward edges of the reefs, and bottom samples were collected in order to learn the effect of drowned valley-harbors in preventing volcanic silt from reaching the seaward reefs. Dr. Joseph A. Cushman has also made use of these bottom samples in his study of the Foraminifera.

A small but excellent collection of fossils from the elevated coral reef at Walu Bay, Suva, Fiji, was presented to the expedition by Coleman Wall, esq., curator of the Fiji Museum, and these were supplemented by a small collection made near Suva, in Fiji, and at Vavao, Tonga, and were studied by Dr. T. Wayland Vaughan.

[1] The report of Dr. Setchell appeared June 6, 1924, as Publication 341 of the Carnegie Institution of Washington.

A few diatoms were collected in Pago Pago Harbor and were studied by Dr. Albert Mann.

As complete a collection of the reef corals as possible was gathered by the Director in Tutuila, specimens being obtained not only in shallow water but also by dredging and diving; and these were transmitted to Dr. T. Wayland Vaughan, under whose direction they were studied by Dr. J. Edward Hoffmeister. Mr. M. N. Bramlette studied the bottom samples from Pago Pago Harbor and material from the boring on the Aua Reef, working also under the direction of Dr. T. Wayland Vaughan.

Lieutenant F. C. Nyland, U. S. N., compiled the data on rainfall and temperature which had been gathered by observers of the U. S. Naval Station at Pago Pago since 1900.

Hon. Josephus Daniels, then Secretary of the Navy, kindly provided the Director with official letters of introduction to Commanders John M. Poyer and Warren Jay Terhune, U. S. N., successively governors of American Samoa, and these gentlemen did all in their power to facilitate our studies and to render our visits to Samoa socially as well as scientifically felicitous. Governor Poyer placed the U. S. S. *Fortune* at our disposal on a journey to Apia in 1918, and in 1919 Governor Terhune gave Professor Daly the use of this vessel to visit the Manua Group, in order to study the geology of these islands. Later it was the privilege of the Director to visit Rose Atoll in the *Fortune*, accompanied by Governor Terhune. In fact, we could not have been more kindly received by the governors of Samoa and the officers associated with them. Luther W. Cartwright, secretary to the governor of Samoa, was most kind in assisting us in many ways.

We were also indebted to the U. S. Department of State for a letter to American consuls in the Pacific, and in response to this Hon. Mason Mitchell, U. S. consul at Apia, Samoa, showed us much kindness and was of decided aid to the expedition. The British Embassy at Washington provided us with a letter to the governor of Fiji, Sir Cecil Rodway, K. C. M. G., who received us kindly, as did also Colonel Logan and Colonel Tate, successively governors of British Samoa.

Not only were officers of the government kindly disposed toward us, but we also owe much to certain corporations and private citizens. Notably Herbert H. White, president of the South Seas Pacific Company, acting upon the suggestion of Professor Henry E. Crampton, placed at our disposal, free of cost, the company's spacious quarters at Pago Pago during the season of 1920. Rev. C. J. Kinnersley, of Leone, entertained Professor Daly and other members of the expedition. To N. Knechtler, esq., the Director is indebted for the photograph of the reef-flat off Faleasau Village, Tau Island, which we have used to illustrate change in direction of wave-fronts in passing from deep into shallow water.

We are indebted to Dr. T. Wayland Vaughan and Dr. J. Edward Hoffmeister[1] for the names of corals. It will be observed that the old and familiar generic name *Madrepora* is replaced by the term *Acropora*, Dr. Vaughan having discovered that,

[1] The Report of Dr. Hoffmeister on "Some Corals from American Samoa and the Fiji Islands" appears as Publication 343 of the Carnegie Institution of Washington.

according to the accepted rules of nomenclature, the term *Madropora* can not stand; but it is with a feeling of regret that we are forced to abandon the use of a generic name which remained unquestioned by four generations of authors during the golden days of systematic zoology.

The expedition was well equipped in apparatus, chemicals, glassware, and supplies. We had a seaworthy gasoline launch capable of circumnavigating the island, a Leeds and Northrup potentiometer and galvanometer for direct determination of hydrogen-ion concentration, and a Wheatsone bridge, induction coil, and tunable telephone for study of the electrical conductivity of sea-water; also a set of colorimetric tubes of thymolsulphonephthalein standardized and presented to us by Professor J. F. McClendon, as well as tubes of phenolsulphonephthalein and methyl red. We were provided with dredges, apparatus for sounding and for gathering bottom samples, and Ekman meters for testing currents. All waters to be tested were contained in bottles of Jena resistance glass.

The borings through the fringing reefs in Pago Pago Harbor were made by a Davis-Calyx drill modified to meet the conditions of soft limestones. Mr. John W. Mills, our chief engineer, devised an improvement in the core-barrel which enabled the apparatus to bring up a core even when boring through soft sand. By use of a diving-hood we were enabled to go down on the outer slopes of the reefs and study the corals at close range; through the use of this diving-hood and submarine camera Professor Longley was enabled to study the habits of the fishes in relation to their coloration.

The natives, while they wholly failed to appreciate the seriousness of our work and regarded the scientific members of the expedition as hopeless but harmless imbeciles engaged in fruitless and foolish tasks, were nevertheless most kind and hospitable. Several times the leading men of some village waded out to us on the reef-flats to suggest that the corals we were collecting were wholly worthless as food and to offer us fish and fruit. In native opinion the most amusing imbecile among us was Professor Daly, whom they named "Ma-a" (the rock), due to his habit of cracking off rocks wherever he went, at the same time muttering such meaningless words as "trachydolorite" and loading himself with a heavy burden of useless objects. Our chief engineer, Mr. John W. Mills, was "Kele Poko" (the Wise One) from the moment he installed the new engine in the hull and made it go. Despite this contemptuous opinion of most of us, the natives showed constant good will toward us, and it is due to Unutoa, chief of Aua Village, that not one of our growth experiments or pieces of apparatus was molested, even though left upon the reefs for months during our absence. A. G. M.

March 18, 1922.

It is inevitable that some expressions and arrangements in these papers should differ from the form they would have had if the author had lived to supervise the work in its progress through the press. However, Professor J. Edward Hoffmeister, of the University of Rochester, an authority on corals, generously consented to examine the page-proofs and he has greatly aided in presenting the volume in good form. If any errors or crudities are discovered, they are not chargeable to Dr. Hoffmeister. W. B.

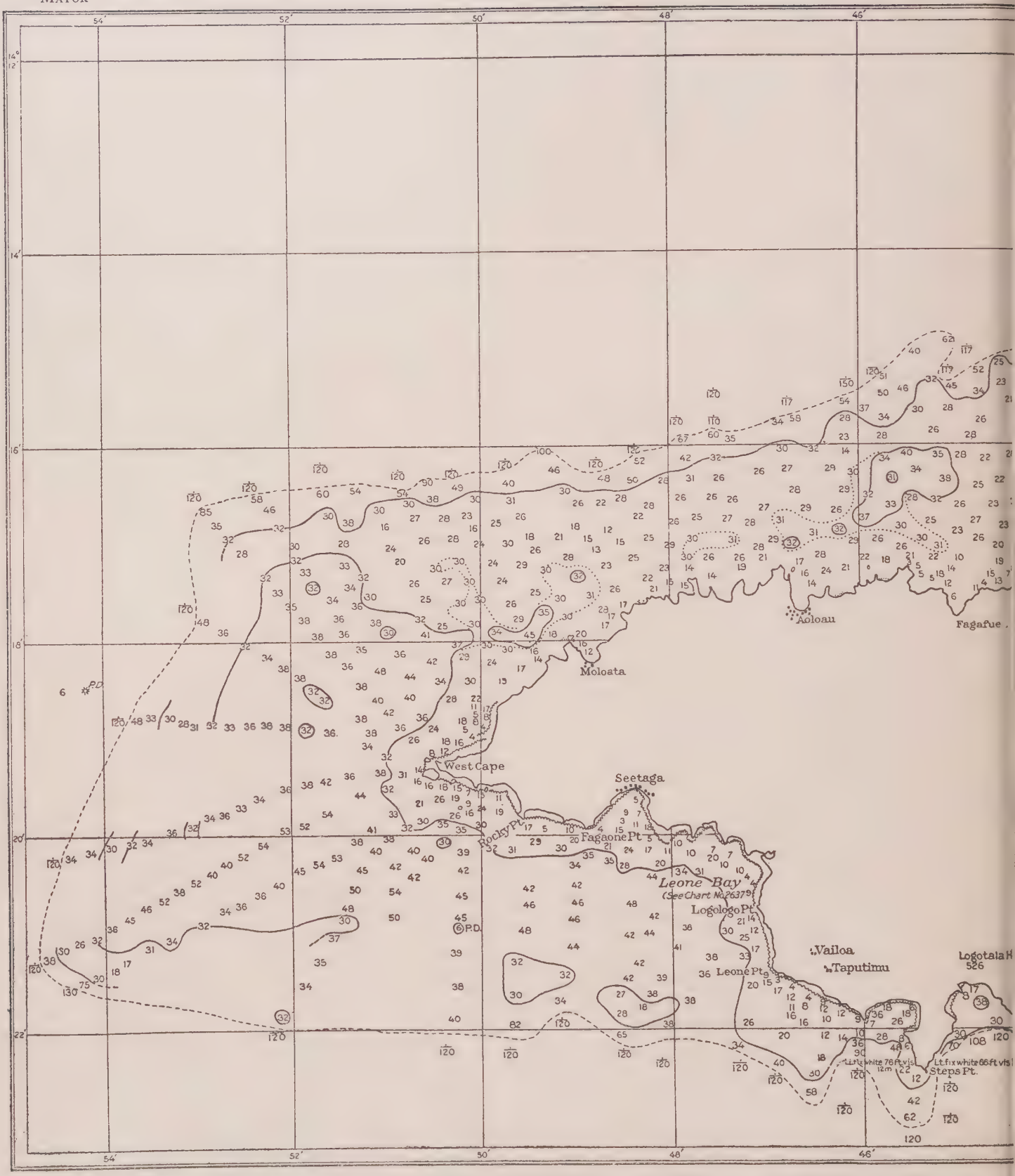
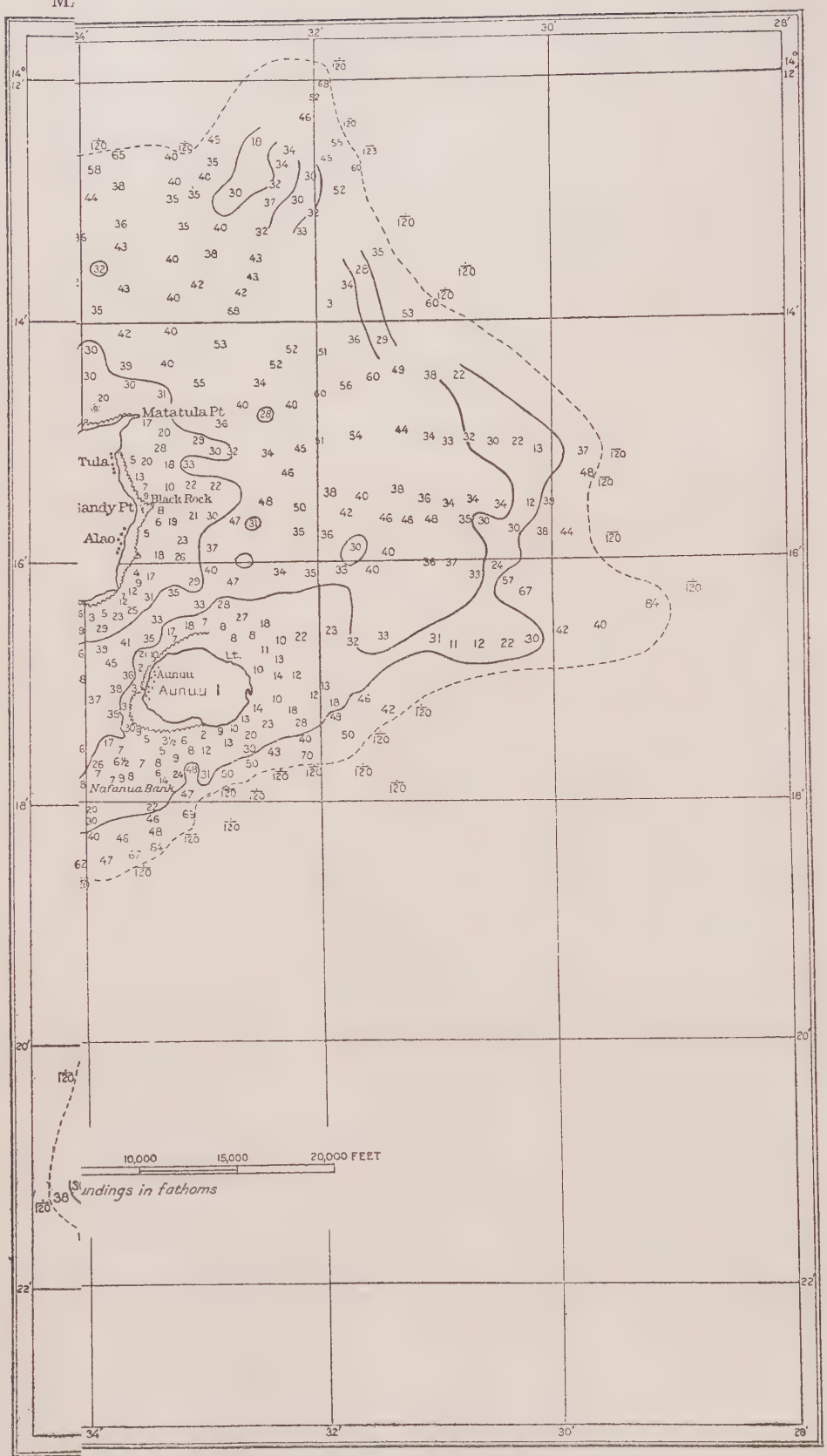


Chart of Tutuila from data of unpublished U. S. Hydrographic Office chart of the island. The submari

orm is contoured at a depth of 32 fathoms to bring out the relation between the ancient barrier and fringing



reefs now submerged and dead. (Soundings in fathoms.)

SOME POSTHUMOUS PAPERS OF A. G. MAYOR RELATING TO HIS WORK AT TUTUILA AND ADJACENT REGIONS

1. Structure and Ecology of Samoan Reefs.
2. Causes which Produce Stable Conditions in the Depth of the Floors of Pacific Fringing Reef-Flats.
3. Inability of Stream Water to Dissolve Submarine Limestones.
4. Growth-rate of Samoan Corals.
5. Rose Atoll, American Samoa.

STRUCTURE AND ECOLOGY OF SAMOAN REEFS.

By Alfred Goldsborough Mayor.

STRUCTURE OF THE SAMOAN REEFS.

With the exception of Rose Island, which is an atoll-rim composed chiefly of lithothamnium, all the Samoan Islands are volcanic. There are no elevated limestones on the volcanic islands of American Samoa, except small tossed-up fragments of the ancient reefs through which some of the tufa cones have burst, as at Aunuu Island, off the southern shore of Tutuila, or the tufa cone near Steps Point, Tutuila, or the crater at Faleasau, Tau Island. An analysis of these limestone fragments by Professor Alexander H. Phillips shows that the ancient barrier and fringing reefs which once surrounded Tutuila, and are now submerged about 180 feet beneath sea-level, are not dolomitized, but have quite the same composition as the modern coral-reefs. The composition of the limestone fragments embedded in the tufa cones of Samoa, as analyzed by Professor Phillips, are given in table 1.

Table 1.

Locality.	Per cent of $CaCO_3$.	Per cent of $MgCO_3$.	Character of specimen.
Aunuu Island, off Tutuila	96.98	1.25	An amorphous mass of limestone.
Tufa cone of Fagalua, near Steps Point, Tutuila	97.21	1.65	Do.
Tufa cone at Faleasau Village, Tau Island, Manua Group (2 specimens)	96.68	0.82	Fossil coral.
	98.28	1.06	Amorphous, chalky-looking mass.

Most of these embedded fragments are amorphous limestone; some show traces of coral calyces, some are crystalline, and one found in the tufa of Aunuu and studied by Professor Setchell was a fossil lithothamnium.

All of the islands of American Samoa are surrounded by a shore bench which is about 10 feet above present sea-level and is backed by cliffs of marine erosion. This bench is especially prominent off the hard basaltic promontories of the islands, where it has been but little cut into by the ocean of modern times, but it extends also along the shores of the drowned valleys which constitute the harbors. This bench is of the same general width of about 200 feet or less around the shores of the islands of the Manua group, as it is around Tutuila, and in both groups of islands it appears to have suffered about the same degree of encroachment by the modern sea. In other words, it seems to have existed simultaneously around all these islands. On Rose Atoll this same bench appears in the numerous large blocks of limestone now nearly all undercut by the sea and lying on the top of the atoll rim. Being undercut, they are all about 5.5 feet high, having lost about 2.5 feet through the process of undercutting. There is no evidence of tilting shown

by this bench on any of the islands of American Samoa, and this leads one to suspect that it may be due to a lowering of sea-level in the modern ocean, the islands having remained stationary during the period. Of course, it may be due to a slight uniform rise in an area of sea-bottom, but this explanation seems unsatisfactory in that the island of Upolu, close to Tutuila, does not show this bench, the shores sloping gradually to sea-level, as if the island had undergone a slight modern subsidence; but it remains a possibility that the bottom itself has been elevated, while Upolu has subsided during modern times to a greater degree than the rise in the sea-bottom upon which it lies; in other words, that its volcanic mass has recently somewhat collapsed, while the volcanic piles of the islands of American Samoa have retained their rigidity and been lifted up bodily by a rise in the sea-bottom.

However, there are many other groups of islands, both in the Pacific and Atlantic, which appear to have emerged above present sea-level within comparatively recent times and now have a narrow sea-bench a few feet above sea-level around their shores, and at the same time show no evidence of local tilting. Such are the atolls of the Paumotos and Ellice groups, the islands of Torres Straits and southeastern Papua, and the Houtman Islands, according to Dakin. (*1*)[1] A comparable emerged shore-bench is seen on the limestone coast of subtropical Florida, along the Florida Keys and in the Bahama Islands, and in many places in the West Indies. Indeed, A. Agassiz, (*2*) who saw more coral reefs than any living man of science, says that "throughout the Pacific, the Indian Ocean, and the West Indies the most positive evidence exists of a moderate recent elevation of the coral reefs"; and R. A. Daly (*3*) records a moderate emergence without tilting along many thousand miles of coast-line, not only in tropical but also in colder regions. Of course, such evidence can not be presented by sandy coasts, such as that between Sandy Hook and northern Florida, nor could such an emerged bench be preserved on coasts where the rock was soft, or where the coast has been rising within recent times, as in California, or sinking, as in Scandinavia, but it would be interesting to know the relative length of the world's coast-lines which show this bench and the length of coast-lines which in so far as we know *should* show it and do not have such a bench. We would gain more from a study of the latter, and an explanation of the absence of the bench than from mere observations of its presence in certain places, for if this bench is due to a general lowering of sea-level it must be present along all coasts composed of the harder rocks, such as granite or basalt, unless these shores have not remained stationary since the time when the bench began to form. At present we can not be certain whether the slight apparent elevation of so many coast-lines is due to actual elevation or to a recent lowering of sea-level.

Professors R. A. Daly and R. T. Chamberlin made careful observations of the emerged shore-bench which extends all around Tutuila, except in the region of the relatively recent lava-flow along the southern shore from Tafuna to beyond Sail Rock, but could find no coral-reef or elevated limestones upon it. Possibly, when this bench was forming, Tutuila had only small, widely separated patches of coral growing around its shores, as have the Marquesas, or the island of Hawaii

[1] The serial numbers in parentheses refer to Literature Cited.

to-day. Certainly the climate of Samoa appears to have been tropical at the time when the bench was formed, for fossil coral and lithothamnium are found in the highest parts of the emerged rim of Rose Atoll.

As Daly pointed out, Tutuila is probably the most ancient of the Samoan Islands and certainly has suffered most from erosion, so that a submerged platform of marine planation, from 1 to 3 miles wide, completely surrounds the island. This platfo·m is composed of redistributed materials derived from the central island itself, as well as of a shelf due to the cutting away of the shores by the sea.

A most interesting fact respecting this old platform, the floor of which is now probably submerged about 400 feet beneath sea-level, was observed by W. M. Davis, (*4*) who noticed that the data for the unpublished hydrographic chart of Tutuila "reveals the existence of a submerged platform from 1 to 3 miles in width and from 30 to 50 or more fathoms in depth," and also that "the outer part of the platform is usually somewhat shallower than at half distance offshore, as if a poorly developed barrier reef inclosed it." Davis, however, failed to observe that not only is there clear evidence of an ancient submerged barrier reef near the outer edge of the platform, but that a well-developed fringing reef of apparently contemporaneous development grew outward from the shores, and at some places, such as on the north coast between Vatia and West Cape, this fringing reef fused with the barrier reef, partially obliterating the lagoon which once existed between the two reefs. That this ancient fringing reef was not a delta plain is evident from the fact that it is generally narrower off the mouths of streams than elsewhere, as a coral reef should be, whereas a delta plain would be widest in such places.

The relation between these ancient barrier and fringing reefs is well brought out by contouring these submerged structures at a depth of 30 or 32 fathoms as is done in plate 7 see Mayor, (*5*) which shows that along the south shore the barrier and fringing reefs were each about half a mile wide, but the ancient fringing reef has been overlaid by a relatively recent lava-flow between Tafuna and Leone.

On the north coast between Vatia and Maloata the fringing and barrier reefs were each about a mile wide and the long narrow channels, which are the remains of the lagoon that once existed between them, appear not to be so deep as is the wide lagoon along the southern coast. The bottom of the lagoon along the northern coast between Vatia and Maloata is not more than 45 fathoms deep, whereas on the southern coast of Tutuila it is in a number of places between 50 and 60 fathoms deep. Thus, as Daly stated, the ancient platform of marine planation may have been submerged by an actual subsidence of the island, which tilted somewhat as it went down, the eastern end and northern shore sinking more deeply than the region along the north coast between Vatia and Maloata. Thus the fringing and barrier reefs along this northern section of the coast, being developed upon a shallower platform, would readily broaden and finally fuse, whereas along the eastern and southern sides of the island, where the platform upon which they grew was more deeply submerged, they remained narrow and did not fuse to such an extent as along the north shore. This explanation is, however, subject to

doubt, for it is not wholly satisfactory to Professor Chamberlin for reasons stated in his report upon the reefs.

The summit of the submerged barrier reef is quite flat and at present sunken to a depth between 25 and 30 fathoms, but here and there a pinnacle or small area of elevation rises abruptly from the sunken ridge and may approach within 11 or 12 fathoms of the surface, as if islets once existed upon the old barrier reef. Indeed, on the Nafanua bank west of Aunuu Island and the Taema bank south of Pago Pago Harbor, patches of coral are now growing upon these elevated places and approach within 4.5 to 6 fathoms of the surface. These patches consist chiefly of living *Acropora*, the fastest-growing of all corals, and there is no doubt that the ancient barrier reef will in time be restored and regain the surface of the sea in these places. Elsewhere, however, it appears to be dead and too deeply drowned for the growth of reef-corals, and its summit is hard and covered with fragments of molluscan shells, lithothamnium, *Halimeda*, etc.

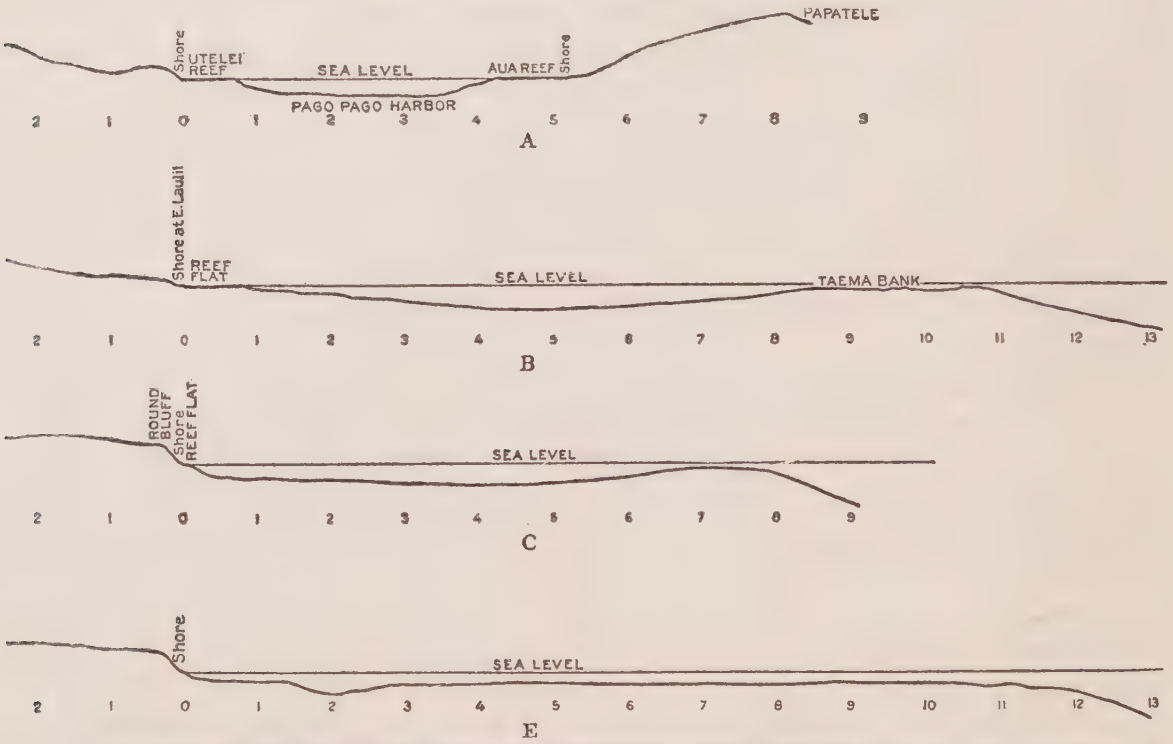


FIG. 1.—Sections across Pago Pago Harbor and across the submerged platform surrounding Tutuila. The vertical scale is same as the horizontal, illustrating conditions as they actually exist.

Text-figure 1 shows sections across the drowned reefs and the ancient platform, derived from data of the unpublished United States hydrographic chart of Tutuila. The vertical scale is the same as the horizontal, thus bringing out the true relations of the old lagoon to the offshore barrier reef and the fringing reef adjacent to the coast.

The bottom of the old lagoon contains soft mud and has apparently been filled in by silt and deposits to a considerable extent, but is still about 50 fathoms beneath the surface, with a few places as deep as 60 fathoms or more. Thus the

reef-wall of the old barrier reef was about 25 or 30 fathoms high, and this would lead one to suppose that the reef continued to grow for a time while the submergence increased, but that finally it could no longer keep within the limits of coral-growth of the surface and died. South of Breaker Point, at the eastern side of the entrance to Pago Pago Harbor, mud from the bottom of the old lagoon, at a depth of 50 fathoms, was gray in color and composed chiefly of foraminifera. Boiling it in hydrochloric acid showed that 95 per cent was soluble and the 5 per cent residue consisted of dark-brown volcanic mud.

It is interesting that a barrier reef should have developed near the outer edge of the ancient submerged platform around Tutuila, while at the same time a fringing reef grew outward from the shore and finally along the northwestern coast fused with the barrier reef. Our ecological studies of corals in the Murray Islands (*6*) and in Samoa show, however, that this is what one should expect, the barrier reef probably being composed chiefly of *Acropora*, which are the fastest growing of all corals, but must have pure agitated ocean-water in which to thrive, and the fringing reef of *Porites*, *Psammocora*, and *Alcyonaria*, which thrive best in water containing silt and away from the direct surge of the breakers.

This barrier reef of Tutuila originated as a barrier reef, as did also the Great Barrier Reef of Australia according to Andrews, (*7*) who showed that the reef was simply a more or less linear series of coral masses growing upon the submerged part of the Australian continental shelf, and that the shelf was not formed by the reef as Jukes, following Darwin, supposed, for the submerged platform continues southward into temperate regions along the Australian coast beyond the geographical limits of coral-growth. Incidentally, we may also state that the submerged continental shelf of Australia extends northward beyond the northern limits of coral-growth, the coral in this tropical region being prevented from growing by the mud from the great rivers of Papua. This very significant discovery by Andrews was destined to quite revolutionize our ideas of the origin of coral-reefs, for soon thereafter Vaughan (*8*) showed that the barrier reef of Florida is growing along the seaward edge of a submerged platform composed largely of oolitic limestone and thus not made by the reef itself, the reef being merely a series of coral patches which have grown during recent times along the outer edge of the submerged shelf. Moreover, as in Australia, this submerged shelf extends into cold regions beyond the geographical range of coral-growth. The barrier reef along the eastern shore of Andros Island, Bahamas, consists also of a series of more or less linear coral patches growing along the outer edge of a submerged platform, but the platform itself is not formed of coral-reef rock.

Moreover, Daly (*9*) showed that the published soundings on charts show that the bottoms of Pacific atoll lagoons are not concave, as Darwin supposed, but remarkably flat and sunken to an average depth of about 20 fathoms, and the reef-wall surrounding the lagoon rises abruptly, almost as if it were a railroad embankment superimposed upon a flat plain. Here again it looks as if the lagoon bottom were a platform of marine planation and the reef-wall a new growth along its edge which accumulated during or after the platform's submergence.

It should be said that Darwin (*10*) had it clearly in mind that barrier reefs might originate as such by the growth of coral along the seaward edge of a submerged platform, but he knew of no examples and regarded the condition as exceptional, although he suspected that some of the West Indian reefs might have been formed in this manner.

The following quotation from Darwin's "Structure and Origin of Coral Reefs" appears to be all of significance that he wrote upon the matter. It will be recalled that there were three editions of his work on coral-reefs—the first in 1842, an enlarged edition in 1874, and in 1889 an edition was published which is merely a reprint of the 1874 edition with an appendix by its editor, Professor Bonney. Darwin died in 1882, but we may quote from the 1889 edition, for the body of the work is identical with that of 1874. In the 1889 edition, page 137, Darwin says:

> A bank either of rock or of hardened sediment level with the surface of the sea and fringed with living coral would be immediately converted by subsidence into an atoll . . . but as we have seen the larger groups of atolls in the Pacific and Indian Oceans can not have been formed on banks of this nature.

Darwin, page 101, 1842, and page 137, 1889 edition, says:

> If a bank lay a few fathoms submerged, the simple growth of the coral without the aid of subsidence would produce a structure scarcely to be distinguished from a true atoll, for in all cases the corals on the outer margin of a reef, from having space and being freely exposed to the open sea will grow vigorously and tend to form a continuous ring, whilst the growth of the less massive kinds on the central expanse will be checked by the sediment formed there.

On page 89 of the 1842 edition he says:

> A reef growing on a detached bank would tend to assume an atoll-like structure; if therefore corals were to grow up from a bank with a level surface some fathoms submerged, having steep sides and being situated in a deep sea, a reef not to be distinguished from an atoll might be formed. . . . I believe some such exist in the West Indies. But a difficulty of the same kind with that affecting the crater theory renders this view inapplicable to the greater number of atolls. (See also p. 120, 1889 edition.)

Darwin, page 48, 1842, and page 66, 1889, says:

> It will perhaps occur to some that the actual reefs formed of coral are not of great thickness, but that before their first growth the sea had eaten deeply into the coasts of these encircled islands, and had thus left a broad but shallow submarine ledge, on the edges of which corals grew; but if this had been the case the shore would have been invariably bounded by lofty cliffs, and not have sloped down to the lagoon-channel, as it does in many instances. On this view, moreover, the cause of the reef springing up at such a great distance from the land, leaving a deep and broad moat within, remains altogether unexplained.

On page 93, 1842, and page 127, 1889 edition, Darwin says that the upheaval and subsequent abrasion of an island would leave a flat disk which might become coated with coral, but not a deeply concave surface. (Darwin believed the bottoms of atoll lagoons to be concave instead of being practically flat, as we now know them to be.)

In four out of these five paragraphs Darwin either casts doubt upon the explanation, or regards it as hypothetical and so exceptional that he can not cite a single instance of its occurrence. Now, however, due to the advance of hydrography and the studies of Andrews, Vaughan, Daly, and Chamberlin, we have reason to believe that what Darwin regarded as the exception is in fact the rule; whereas his main thesis that "atolls have been formed during the sinking of the land by the upward growth of the reefs which primarily fringed the shores of ordinary islands" remains unproven.

Professor W. M. Davis (*11*, p. 564) says in his criticism of Chamberlin that there is "no doubt that when the now submerged barrier reef of Tutuila was first formed at a distance of a mile or two from the cliffed inner border of the shallow supporting platform it would have been classed by Darwin as a fringing reef because the enclosed water channel was then of small depth." Now Professor Davis presents only half the actual facts to this hypothetical Darwin, for, as Chamberlin shows, we have reason to believe that contemporaneously with the development of the offshore reef there grew also another reef attached to and extending along the shore of Tutuila. Darwin, who never flinched before a fact to maintain a theory, would certainly have called this shore reef the fringing reef and the offshore reef could then have been nothing but a barrier, no matter whether the lagoon was shallow or deep. Moreover, Darwin would doubtless have seen that the offshore reef had grown near to but at an appreciable distance inside the seaward margin of a submerged platform of marine planation and that in many places the reef simply lies upon the platform as if it were a mere embankment, the platform extending under it and reappearing on the seaward side of the reef. Darwin would doubtless have said that here at last was an example of a condition he had never been able to find, and which he had thought of more as a theoretical possibility than as an actuality. He would probably have concluded that the old barrier reef of Tutuila showed no evidence of ever having been a fringing reef, but had developed independently, while a true fringing reef grew along the shore, and thus his thesis of fringing reefs being converted into barrier reefs did not apply to Tutuila. Curiously, even Professor Davis (*4*) himself in 1918 called this outer reef a "barrier reef," but appears quite willing to have his "Darwin" do otherwise.

The crux of Darwin's theory is concisely expressed by him on page 147 of the 1842 edition of his classic work on coral reefs, and also on page 194 of the 1889 edition, in the following words:

> On this view [that of prolonged subsidence] every difficulty vanishes; fringing reefs are thus converted into barrier reefs, and barrier reefs when encircling islands are thus converted into atolls, the instant the last pinnacle of land sinks beneath the surface of the ocean.

It is true that Darwin's definition of "fringing reefs" is unfortunately vague in that it confuses them with barrier reefs. He says (p. 4, 1889 edition) that fringing reefs "differ from barrier reefs in not lying far from the shore, and in not having within them a broad channel of deep water," but how deep and how broad the channel may be and the reef still be a fringing reef he does not say.

Of course, all reefs begin as a series of coral patches which through growth fuse into a solid structure and, in the case of fringing reefs, extend straight out from the shore, so that at low tide one may wade from the beach to the seaward edge of the reef. If a Pacific fringing reef be exposed to heavy breakers, lithothamnium grows along its seaward edge and raises this part a few inches above low-tide level, thus making a ridge along the seaward edge, and favoring the development of tide-pools on the shoreward parts of the reef. Where the breakers become spent, about 200 to 400 feet inward from the seaward edge, the *Lithothamnium* dies out, and here the ridge disintegrates into jagged limestone masses which become detached and are washed shoreward over the reef-flat by the surges. Corals grow so readily upon these erratic fragments of the lithothamnium ridge that most of the coral-heads of the shoreward parts of the reef-flat are attached to them. Thus most of the corals growing on such a reef-flat are actually loose and liable to be driven ashore in time of exceptional storm. Of course, in regions where storms are common, or where the average surf is so heavy that it drives straight over the reef-flat to the beach, small loose fragments can not long remain upon the reef-flat, which then becomes smoothly veneered with *Lithothamnium*, thus protecting it from destruction by the sea. There are, however, always many tide-pools and crevices in which living coral-heads cluster, and the top of the reef-flat is usually a rich collecting-ground for corals.

We see, then, that while fringing reefs begin as isolated coral patches, these soon coalesce and the whole reef becomes backed up against the shore. Due to this backing afforded by the shore, fringing reefs in somewhat protected situations can be composed of looser and less compacted materials than can a barrier reef over which the surges dash in full force. In any event, a typical Pacific fringing reef has no lagoon between it and the shore, unless indeed we call such the very shallow tide-pools, rarely more than a foot deep, which may be impounded back of the lithothamnium ridge. Darwin's chapter on fringing reefs is unfortunately vague, and in the three editions of his work the reefs of the Florida-West Indian regions are all classed as "fringing reefs," although such well-developed barriers as the reef of Yucatan, the Florida reef from Miami to beyond Key West, and the reef on the eastern side of Andros Island are found here. Moreover, in the midst of the Bahamas lies one of the most beautiful little atolls in the world, Hogsty Reef.

However, as Professor Davis says, if we take Darwin's theory as Darwin himself proposed it, we must accept his vague and unsatisfactory definition of fringing reefs; but even so it has not been proven that the rim of a single modern atoll was ever a fringing reef in Darwin's sense or even a barrier reef. Darwin labored under great disadvantages. He saw only a few of the Society Islands and only one atoll, Cocos Keeling. There were almost no published soundings in lagoons in 1842, and the significance of drowned valleys in indicating submergence or subsidence had later to be explained by Dana. Darwin's theory, as he advanced it, presupposes subsidence of the land rather than an elevation of sea-level, nor could he, in the absence of soundings, grasp the importance of submerged platforms of marine planation which we now begin to realize are of

paramount significance in determining coral-growth. To Darwin's mind, coral-growth was probably continuous through long periods, but we now know that the reverse was the case. Thus Vaughan (*12*) shows that in the West Indian-Florida regions there was a maximum development of coral reefs in the middle Oligocene, when at least 15 genera now confined to the Pacific and Indian Oceans existed on the tropical Atlantic reefs. In Miocene and Pliocene times the Florida-West Indian reefs were poorly developed, no Pliocene reefs being known from the West Indies. Later in Pleistocene and Recent times there has been a fair development of reefs in this region, but the number of genera has become reduced, such forms as *Pocillopora*, *Pavona*, *Favites*, *Goniopora*, *Goniastrea*, *Galaxea*, *Stylophora*, and *Alveopora*, and 7 others of less importance, having disappeared from the West Indian region before Pliocene times. It is of interest to see that during the glacial period there was a better development of West Indian reefs than in the Pliocene, and in general reefs developed best during times of subsidence.

The strongest point in favor of Darwin's theory of subsidence is the great thickness of the ancient elevated reefs in Fiji, Tonga, the New Hebrides, and elsewhere in the Pacific. In many of these elevated masses of limestone the corals are superimposed and in place for hundreds of feet, and all the evidence supports the view that the reef grew upward and maintained itself at or near the surface while the substratum sank. It seems certain from the accounts of Davis (*13*) and others that some of these elevated reefs in the New Hebrides were atolls, but elsewhere they have suffered so much erosion that it may be impossible to interpret their past history. Possibly some of them were atolls which had developed to the final stage in which the lagoons had become practically filled in by materials from the reef. At present, despite the good work which has been done upon the elevated reefs of Fiji by Andrews (*14*) and Foye, (*15*) we can not be certain of their age in relation to the age of Atlantic reefs bearing similar fossils, and we know but little of their intimate structure.

In considering Darwin's theory, we should bear in mind how difficult it would be to change a fringing reef into a barrier reef through subsidence. If the fringing reef were drowned so deeply by subsidence that its corals were killed, it is obvious that it could not afford a substratum for the growth of a barrier reef, and a new fringing reef would develop along the shore. If, on the other hand, the subsidence was moderate, the corals which grow in abundance all over the broad upper surface of the fringing reef would at once spring up toward the surface, while fragments from the reef would tend to fill in any lagoon which might be left between the reef and the shore, especially as these lagoons would usually be narrow, due to the steep slopes of most volcanic islands. It would seem that only under exceptional conditions, such as abnormally gradual slopes of the shores of the central island, could a fringing reef be converted into a barrier by subsidence; but that successive periods of relatively rapid subsidence followed by periods of relative stability would lead to the development of a series of step-like terraces of successive fringing reefs.

But to return to the subject of the reefs of Tutuila. After the old barrier and fringing reefs had been killed by drowning, the island became deeply sub-

merged, as explained by Chamberlin, and the sea remained at this high level during so long a period that shore-cliffs nearly 300 feet high were cut, as at Round Point (plate 5, fig. A).

Chamberlin and Daly could find no evidence of the existence of coral reefs on Tutuila at this time of greatest submergence, and it seems probable that there were then only small isolated patches of coral around the island, as along the shores of the Marquesas to-day.

The living reefs of Tutuila did not begin to grow until after the island had emerged to its present level, probably by a lowering of sea-level rather than through an actual elevation of the land. They are simple fringing reefs projecting seaward from the shore, although in many places, as off the promontories of the north shore, there are coral patches composed chiefly of *Acropora*, but they have neither reached the surface nor constituted a continuous reef.

The fringing reef is widest on the sides of the bays and in places where the submarine slopes are relatively gentle, but at the promontories, where the slopes are steep, the reef is narrow or does not exist.

Along the south shore, where the reef is exposed to the breakers caused by the trade-wind, the lithothamnium ridge is well developed and in many places the reef-flat grows up to low-tide level, but the north shore is protected from the trades, although a surging sea swings around the island and keeps the water fairly rough; but the lithothamnium ridges of the reefs in these north-shore harbors are rather poorly developed, and the reefs are narrower than on the south shore and confined to the sides and inner ends of the harbors.

In some places, as on the west side of the entrance to Vatia Harbor, the reefs have suffered great destruction from a hurricane, no tradition of which is retained by the natives. Great numbers of corals were thrown up to a height of about 8 feet above low tide, and now lie a hundred feet or more inland, with full-grown *Barringtonia* trees covering them. Yet the reef-flat in this place has not yet recovered and lies submerged at all tides, with no lithothamnium ridge. For the lithothamnium ridge is everywhere chiefly composed of dead *Acropora leptocyathus*, which, having grown and died, is held in place and veneered by lithothamnium, thus causing it to remain as a permanent accession to the seaward edge of the reef-flat. The lithothamnium itself grows so slowly at tide-level that it alone would not form a ridge were it not for the fact that it quickly covers, smooths over, and cements upon the reef-flat all corals which have died, thus securing the retention of any accession of limestone which the seaward edge of the reef may have once attained. The lithothamnium itself is thus merely a cementing, binding, veneering, smoothing, and wave-breaking sheet which covers and preserves to the reef the limestone formed by the dead coral which once grew upon it.

The upper surface of the reef between Blunt's Point and Fagaalu, Pago Pago Harbor, has also suffered practical annihilation of its corals through some forgotten hurricane and has not yet recovered. It will be recalled that F. Wood Jones (*16*, p. 122) records the sudden destruction of a large area of corals in Cocos Keeling Atoll in 1876 and their failure to regain their foothold after 30

years. Also at Tortugas, Florida, the *Acropora muricata* which once flourished over the reef-flats in great abundance was killed by the so-called "dark water" of October 1879, and even yet (1922) this coral is rare or absent over the areas in which it was once the dominant form. Vaughan (*17*) showed that coral planulæ may remain floating for days rather than settle in unfavorable conditions, such as stale water, and it seems possible also that planulæ may prefer to settle in regions wherein many coral-heads of their own species are growing rather than on barren areas.

The fringing reef of the south shore of Tutuila is interrupted by the relatively recent lava-flow which extends from the Nuuli Lagoon to Sail Rock. This lava overwhelmed the ancient shore-reef and the elevated wave-cut bench, but is itself strongly clipped by the modern sea. In many places near the shore it shows the ropy surface seen in modern pahoihoi flows of Hawaii. In fact, the surface of this ancient Tutuila lava near the sea shows less effect from erosion than does the Kahuku lava-flow of 1868 on Hawaii, but, as was suggested by Professor Thomas Jaggar, the fresh appearance of the Tutuila flow is deceptive and due to the spray washing off the decomposed surface layer, thus exposing underlying layers which have not yet been weathered.

Off Nuuli the fringing reef is fully 3,000 feet wide, but elsewhere it is much narrower, none of the reefs in Pago Pago Harbor being much more than 1,000 feet wide.

By throwing out a heavy anchor on the extreme seaward edge of the reef, and having attached to this anchor a line with distances measured off on it, we succeeded in making soundings at 25 or 50 foot intervals off the seaward edges of the reef-flats. The results are shown in table 2 and illustrated in figure 2, wherein the vertical scale is the same as the horizontal, thus giving a picture of the submarine slopes as they actually are.

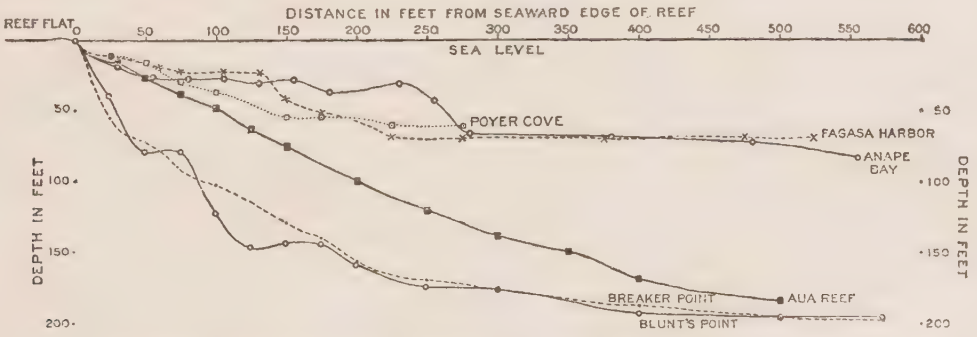


FIG. 2.—Soundings off seaward edges of reef-flats of Tutuila. The vertical scale is same as the horizontal, thus showing actual conditions. The harbors of the north coast are not so deep as Pago Pago Harbor.

The seaward edge of the reefs at low-tide level usually overhangs as a shelf, due to the growth of *Acropora leptocyathus*, veneered with lithothamnium. Below this projecting shelf lies a precipitous slope, usually of from 2 to 5 fathoms, and below this coral-heads, especially *Acropora* and *Pocillopora*, cluster thickly, producing a very irregular surface. These reef-building corals do not thrive at depths

below 8 fathoms in Pago Pago Harbor, where the water is calm and silt forms readily, but in the agitated ocean-water of the outer coasts the reef-corals grow at depths well below 10 fathoms, although their heads are not so large as in shallower water. In Pago Pago Harbor such "intermediate corals" as *Leptoseris* and *Fungia Patelliformis* come up to within 12 to 14 fathoms of the surface, but on the ocean slopes of the island reef-corals grow well at this depth, due to the agitation of the water of the coast.

TABLE 2.—*Soundings off seaward edges of fringing reefs of Tutuila Island, Samoa.*
Illustrated by figure 2.

Distance in feet from outer edge of reef.	Depth in feet.					
	Poyer Cove off SitaVillage, north coast of Tutuila, 280° true from eastern promontory at mouth of cove.	From middle of eastern side of Fagasa Harbor, north coast of Tutuila, 285° true.	From inner end of Anape Bay near western waterfall, 340° true, north coast of Tutuila.	From outer end of Aua Line, Aua Reef, Pago Pago Harbor, 247° true.	From 900 feet north of Breaker Point, Pago Pago Harbor, 249° true.	From Blunt's Point, Pago Pago Harbor, 57° true course.
25	12	12	....	15	54	39
30	....	...	18	...	...	...
50	15	...	....	21	72	79
55	....	...	27	...	...	...
60	....	18	....	...	...	...
75	30	21	....	39	90	79
80	....	...	27	...	...	...
100	36	...	....	48	102	123
105	....	21	27	...	...	...
125	39	...	....	63	...	147
130	....	24	30	...	...	...
150	54	42	....	75	129	144
155	....	...	27	...	...	...
175	54	51	....	...	...	144
180	....	...	36	...	...	...
200	....	...	....	99	156	159
225	60	69	....	...	...	...
230	....	...	30	...	...	...
250	....	...	....	120	168	174
255	....	...	42	...	...	...
275	60	69	....	...	...	...
280	....	...	66	...	...	...
300	....	...	....	138	177	177
350	....	...	....	150	...	...
380	....	69	69	...	...	...
400	....	...	....	168	186	192
475	....	69	....	...	...	...
480	....	...	72	...	...	...
500	....	...	....	183	195	195
555	....	...	84	...	...	...
575	....	69	....	...	198	195

The talus-slopes of the reefs in Pago Pago Harbor extend below 10 fathoms and are of about 30°, this being apparently the angle of repose of the fragments of broken and dead coral which compose them. These talus-slopes gradually lose themselves in the relatively flat bottom of the harbor, which is covered with mud and must have been greatly filled in. At the inner end of Pago Pago Harbor this

bottom mud is brown in color and only 33 per cent by weight of it is soluble in boiling hydrochloric acid, the residue being a fine brown volcanic mud. At the mouth of the harbor, however, 94 per cent of the bottom mud is soluble in boiling hydrochloric acid and only 6 per cent is composed of this brown volcanic silt.

Using a Davis-Calyx drill, our chief engineer, Mr. John W. Mills, made four borings through the fringing reef of Pago Pago Harbor, at the same time devising an improvement in the core-barrel which permitted even loose sand to be brought to the surface from the bottom of the boring. Three of these borings were made under the direction of Professor L. R. Cary to facilitate his study of the *Alcyonaria* of the Utelei Reef. At the bottom of all borings we ran suddenly into hard, apparently wave-worn, unweathered basalt. On the Utelei Reef this basalt was encountered at a depth of 68 feet at 200 feet from shore, 121 feet at 575 feet from shore, and 120 feet at 925 feet from shore.

A boring was also made on the Aua Line of the Aua Reef 512 feet from shore and basalt was encountered at a depth of 156 feet. This Aua Reef, being more fully exposed to the breakers than the reef of Utelei, is composed of more compact and solid material, relatively little sand being met with in the boring. When the boring had gone down 65 feet, 50 feet of 4-inch inside diameter steel pipe was driven down as a casing. The material brought up in the core-barrel from various depths was treated with boiling hydrochloric acid with results as shown in table 3.

TABLE 3.—*Boring on Aua Reef.*

Depth from which material was brought up in the core-barrel.	Per cent by weight which was soluble in boiling HCl.	Per cent by weight of brown volcanic mud insoluble in boiling HCl.
feet.		
65	99.4	0.6
118	98.5	1.5
125	83.2	16.8
152 to 156	98.4	1.6

Thus, at a depth of 125 feet, a considerable amount of volcanic silt appears to have settled over the reef, possibly due to heavy rains or to changes in the position of the mouth of the stream which now flows into the harbor at Aua Village.

The surge of the southeast trade-winds drives pure ocean-water into Pago Pago Harbor; it drifts inward along the eastern shore, and to counterbalance this the harbor-water drifts out to sea along the western shore. Thus the reefs of the eastern side of the harbor are composed largely of *Acropora*, a pure-water coral, whereas those of the western shore have *Porites* as an abundant if not a dominant element, for *Porites* grows best in slightly silted or impure water. It is interesting to see, however, that the reefs of the western shore are quite as wide as those of the eastern, thus making it seem that a reef composed largely of *Porites* may grow as rapidly as one composed chiefly of *Acropora*. *Porites*, while it grows somewhat more slowly than *Acropora*, produces more rigid stems, and in rough water it thickens and strengthens its stems more readily than does *Acropora*.

Moreover, the massive forms of *Porites* add a practically indestructible element to the reef. Thus a *Porites* reef may build more surely than one composed of fragile-stemmed *Acropora* and in the end be quite as rapid a reef-builder as the more rapidly growing *Acropora*.

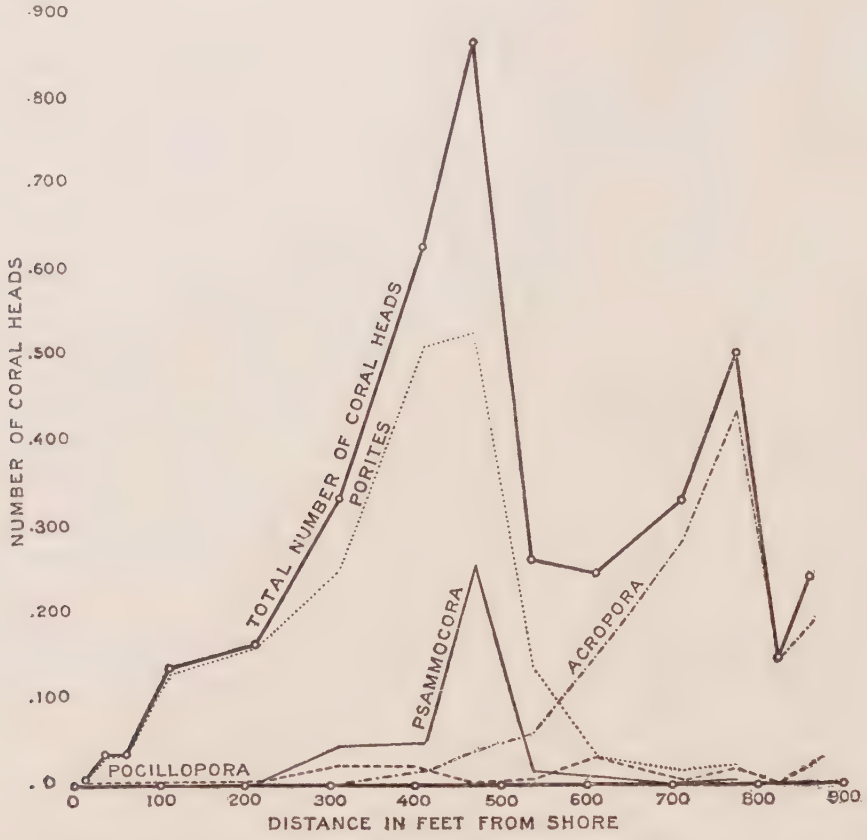


FIG. 3.—Number of coral-heads over the Aua line at various distances from shore to reef-edge. *Porites* are most abundant near shore, *Acropora* near outer edge of reef, *Psammocora* in middle; *Pocillopora* is widely distributed.

II. ECOLOGY OF THE AUA CORAL-REEF, PAGO PAGO HARBOR.

A line 885 feet long, which we will call the Aua Line (see sketch-map of Pago Pago Harbor, plate III), was surveyed and marked at 100-foot intervals by iron stakes across the reef-flat off the southern end of Aua Village on the eastern side of Pago Pago Harbor. The line starts from a large "Pua tree" (*Fragræa bertenana*) on the sandy beach, and in 1917 ran south 39.5° west (magnetic) to the most conspicuous erratic, storm-tossed coral rock on the outer edge of the reef, marked "coral block 3 ft." on the chart of Pago Pago Harbor, U. S. Hydrographic Office, No. 2563.

Plate IV, fig. A, shows this coral block at the seaward end of the Aua Line and the lithothamnium ridge around it. Plate IV, fig. B, is a view from the shore across the Aua Line, the position of the line being shown by the heavy straight line drawn across the picture. Plate V, fig. A, represents the region of branched *Acropora* back of the lithothamnium ridge, at low tide; and plate V, fig. B, shows

the extreme outer edge of the lithothamnium ridge with *Acropora leptocyathus* clustering over the surface. Figure B, plate VI, shows the derrick used in boring through the Aua Line 512 feet from shore in July 1920, the view being taken from the crest of Papatele precipice above the reef. The small black object near the center of the reef-flat is the derrick.

TABLE 4.—*Depth and character of bottom over the Aua Line.*

Distance in feet from shore.	Depth in inches at low tide of the new moon spring tides.	Character of bottom.
Low-tide line	0	Sandy beach 97.5 per cent calcareous, 2.5 per cent volcanic, or insoluble in boiling hydrochloric acid.
10	8	Fine white limestone sand, with scattered patches of nullepore algæ, and a few small loose blocks of dead coral. Very few corals, and these all small, and only on erratic limestone rocks that have been driven shoreward in time of storm. A few dark Prussian-green-black holothurians, *Stichopus chloronotus*.
50	10	Bottom similar to that 10 feet out, but with more holothurians, less algæ, and more coral-heads, nearly all of which are species of massive *Porites*, and all small in size, being rarely more than 3 inches in diameter. *Pocillopora* also survives here.
100	8.5	Sandy with little or no seaweed. Massive branched *Porites*, fairly numerous; all attached to loose limestone boulders that project above general level of sandy floor. Holothurians numerous.
200	2.5	Erratic dead coral rocks more numerous than at 100 feet from shore, but limestone sand still predominates. The sand consists of rather fine particles. Corals not very numerous; chiefly massive and branched *Porites* with many holothurians. Very few branched *Acropora* and all of these on loose, erratic dead coral rocks which were driven shoreward in time of storm.
300	6	Patches of limestone sand and dead coral rocks covering about equal areas over the bottom. The corals are *Porites*, *Psammocora*, and *Pocillopora*, and very few *Acropora*.
400	7.25	Branched *Porites* very numerous. *Acropora* rare. Bottom chiefly fragments of dead coral lying loosely over the surface and with patches of limestone sand in the crevices. *Porites* dominant. Coral-heads most densely crowded about 475 feet from shore.
500	11.75	Deepest part of reef-flat near this region. Sandy patches and fragments of dead and broken *Acropora* about equal in area to each other over the bottom. Erratic dead coral boulders neither so large nor so numerous as at 600 feet from shore. *Psammocora* reaches its maximum about 450 feet from shore. Corals not very abundant. Slender long-branched *Acropora* and large massive *Porites* are the commonest corals, projecting above the sandy floor.
600	10.25	Region of slender *Acropora* with long branches. *Porites* not common. Bottom covered with patches of coarse coral sand and fragments of dead *Acropora*, the sand patches being predominant. Many small and a few large erratic boulders of dead coral, some of which project above surface at low tide of spring tides.
700	6.25	Zone of branched *Acropora formosa*, etc. These branched *Acropora* attain a maximum about 750 feet from shore. Bottom covered thickly with fragments of dead *Acropora* with very little sand, and this only in crevices. Erratic coral blocks, smaller but more numerous than at 800 feet from shore. The surge of breakers in ordinary weather dies out at low tide in this region about 700 feet from shore. Holothurians rare.
800	Awash	Zone of dark brown *Acropora samoensis*. Bottom irregular, hard, jagged, and rocky, without sand, and with very large erratic dead coral boulders washed inward from outer edge of reef. No small erratic boulders. Very few *Porites*. Very little lithothamnium.
870	About 6 ins. *above* water.	This is the region of the lithothamnium ridge. Bottom hard smooth rock veneered with lithothamnium. No loose erratic boulders here, either large or small, except a few large ones caught and held in crevices. The breakers dash hard upon this ridge and the short stumpy incrusting *Acropora leptocyathus* is the dominant coral, being the only one able to withstand the dash of the breakers.

Squares 24 feet on the side were staked out at intervals along the surveyed line over the Aua Reef. Each square inclosed 576 square feet, and all coral-heads,

millepora, alcyonaria, and holothurians found upon it were recorded. The position of these squares and the number of coral-heads, etc., found within them are recorded in table 5, illustrated by text-figure 3.

TABLE 5.—*Number of living coral-heads upon each of the 24-foot squares on the Aua Line in Pago Pago Harbor, Tutuila, Samoa, in March and April 1917. (Illustrated by text figure 3).*

Name of coral.	Distance in feet from the low-tide line of the shore.														
	0 to 24.	24 to 48.	48 to 72.	100 to 124.	200 to 224.	300 to 324.	400 to 424.	460 to 484.	526 to 550.	600 to 624.	700 to 724.	766 to 790	812 to 836.	850 to 874.	Total.
Massive Porites allied to P. lutea	6	32	31	97	82	94	190	205	90	32	18	23	....	....	900
Branched Porites, P. andrewsi	....	....	2	32	79	157	317	319	49	2	....	....	....	....	957
Psammocora	....	2	....	....	2	46	49	259	17	9	1	5	....	....	390
Pocillopora (3 species), chiefly P. damicornis	3	2	2	4	3	24	23	3	6	35	5	19	....	31	160
Pavona (2 species), P. frondifera and P. decussata	....	....	....	....	....	2	1	22	35	10	7	4	....	....	81
Leptastrea purpurea	....	1	....	3	1	7	4	10	....	....	....	....	....	....	26
Favites	....	....	....	2	1	....	....	....	....	2	....	....	1	....	6
Branched Acropora related to A. muricata	....	....	....	....	....	3	13	38	59	151	265	407	....	....	936
Brown-stemmed coarsely branched Acropora shown in plate IV A	....	....	....	....	....	....	....	....	....	....	1	4	144	8	157
Delicately branched Acropora allied to A. formosa	....	1	....	....	....	....	2	2	....	....	16	15	....	15	51
Acropora samoensis	....	....	....	....	....	....	....	....	....	....	....	13	....	1	14
Encrusting Acropora, A. leptocyathus (see plate V)	....	....	....	....	....	....	....	....	....	....	....	....	....	160	160
Goniopora	....	....	....	....	....	....	....	....	2	....	....	....	....	....	2
Lepturia	....	....	....	....	....	....	....	....	....	....	1	....	....	....	1
Galaxia fascicularis	....	....	....	....	....	....	....	....	....	....	....	....	1	....	1
Merulina	....	....	....	....	....	....	....	....	....	....	....	1	1	....	2
Fungia	....	....	....	....	....	....	....	....	....	....	1	....	....	....	1
Montipora	....	....	....	....	....	....	....	....	....	....	....	13	....	21	36
Massive Montipora	....	....	....	....	....	....	....	....	....	2	2	....	....	....	2
Foliated Montipora	....	....	....	....	....	....	....	....	....	....	4	....	....	....	4
Hydnophora microconos	....	....	....	....	....	....	....	....	1	....	1	....	....	....	2
Cyphastrea	....	....	....	....	....	....	....	1	1	6	2	....	....	....	10
Pavona divaricata	....	....	....	....	....	....	....	....	....	....	1	1	....	....	2
Millepora	....	....	....	....	....	1	2	4	....	....	2	....	....	....	9
Number of heads on each square	9	38	35	138	168	334	601	863	262	247	327	505	147	236	3,910
Number of species on each square	2	5	3	5	6	8	9	10	10	8	15	11	4	6	.....

TABLE 6.—*Alcyonaria, blue-black holothurians (Stichopus chloronotus), and blue starfishes (Linckia lævigata) on the Aua Line, Pago Pago Harbor, Tutuila, Samoa.*

Name.	Distance in feet from low-tide line of the shore.														
	0 to 24.	24 to 48.	48 to 72.	100 to 124.	200 to 224.	300 to 324.	400 to 424.	460 to 484.	526 to 550	600 to 624.	700 to 724.	766 to 800.	812 to 836.	850 to 874.	Total.
Alcyonaria	....	1	2	6	3	2	....	5	....	....	....	....	3	....	22
Blue starfishes	....	....	....	....	1	....	1	....	....	....	....	....	....	....	2
Blue-black holothuria	25	68	83	101	183	115	170	135	34	12	4	3	....	....	935

At Murray Island, Queensland (Mayor, *6*), and also in Samoa, the densest clustering of coral-heads is found in relatively quiet water, about 150 to 200 feet inward from the region wherein the surges die out in ordinary weather. The greatest number of *kinds* of corals are, however, found on both reefs just where the surges die out in ordinary weather.

TABLE 7.—*Percentage compared with entire number of coral-heads found on reef-flat.*

Genus.	Murray Island, Australia.	Aua Reef, Pago Pago, Samoa.
Porites.....	38	47.4
Acropora.....	18	33.6
Pocillopora.....	10	4.1
Psammocora.....	very rare	10
Seriatopora.....	25	0
Total.....	91	95.1

Again, in both the Australian and the Samoan reefs, according to Mayor (*18*), 4 genera comprise more than 90 per cent of the entire number of coral-heads found on the reef-flat (table 7).

In both cases *Porites* are the most abundant corals, although not so conspicuous as *Acropora* with its large individual heads and long stems. *Seriotopora* is not found on the Samoan reef, but, from an ecological standpoint, its place is taken by *Psammocora*, which, like *Seriatopora*, is most abundant in the middle regions of the reef-flat, where rough water can not shatter its fragile stems.

Although in essentials, mentioned above, these Australian and Samoan reefs are similar each to each, yet in slight respects they differ, for at Aua the nodular *Porites* grows within 15 feet of low-tide line, just beyond the influence of seepage of fresh water from the shore in time of torrential rains, whereas at Murray Island there are practically no corals within 200 feet of the shore. This is probably due to the strong current of about 20 or more feet per minute which moves along parallel with the shore over the Aua Reef, thus bringing in pure ocean-water and food from Breaker Point. Moreover, the reef-flat at Murray Island is impounded and converted into a vast tide-pool at practically every low tide, whereas at Aua it is impounded only by the lowest of new-moon spring tides, which at most occur only 3 or 4 days in the month. Thus the shore-water of the Murray Island reef-flat is relatively more stagnant and more readily heated by the warmer suns of Australia than is the Samoan reef, and in this manner the apparent difference between the two reef-flats may readily be explained.

The number of species of corals is greater in Australia, and there seem to be more of the rarer forms than in Samoa. Thus I list only 15 genera from the Aua Line, whereas the line across the Murray Island Reef gave 24.

Acropora are relatively less abundant on the Murray Island Reef than on the Aua Reef, but this is due to the remarkable growth of *Seriatopora*, which in the middle region of the Murray Island Reef crowds out the other corals. On the Aua Reef *Psammocora* occupies somewhat the same ecological position but is not so successful in usurping the field as is the *Seriatopora* of the Australian Reef.

As in Murray Island, so on the Aua Reef, the *Acropora*, which are easily killed by heat or smothered by silt, live on the outer parts of the reef, where the water is pure and cool, while the *Porites*, which are relatively resistant to heat or to silt, live near shore. Thus experiments made upon corals placed in warm sea-water

heated and maintained at definite temperatures in a thermostat chamber showed that a temperature of 34.4° C. for 30 minutes or of 35.3° for 20 minutes will kill the branched *Acropora formosa*, but the brown-colored, "stumpy," short-stemmed *Acropora leptocyathus*, which grows in rough water about 700 feet from shore, although seriously injured by these temperatures, usually survives. The very profusely, delicately branched *Acropora hyacinthus* which forms expanded "fungus-shaped" or vase-shaped colonies, especially in water just below the influence of the breakers or in relatively protected parts of the reef-flat, where pure, cool water surrounds it, is about as resistant as the brown-stemmed, coarsely-branched *Acropora samoensis* and is killed by exposure to 35.8° C. for 30 minutes. The most resistant species of *Acropora* is, however, the low-lying, stumpy-stemmed incrusting *Acropora leptocyathus*, which thrives where the breakers pound in full force upon the outer edges of the reef-flat. It survives 30 minutes of 34.4° C., but is seriously injured if not killed by an equally long exposure to 35.8° C.

As a temperature of 32.3° C. was observed in the water of the Aua reef-flat at the low spring-tide of March 22, 200 feet from shore, at a time when a gentle breeze rippled the water, it is possible that in bright sunshine, with the reef-flat impounded for 3 hours by an unrippled calm, the temperature near shore might rise to 34.4° C., which in half an hour would be fatal to the branched species of *Acropora formosa* or to *Acropora samoensis*. Thus inability to withstand heat may account for the almost total absence of *Acropora* within 150 feet of the shore, but they are also very sensitive to silt, and this is an additional reason for their absence from the shore region. Wood Jones (*16*, p. 124) says that in Cocos Keeling *Acropora* thrive in tide-pools which become heated to 93° F. (33.9° C.).

TABLE 8.

Name of coral.	Constant temperature, exposure to which causes death in one hour.	Relative rate of oxygen consumption per gram of living substance at 29° C.
	° C.	
Acropora muricata.....	3.7	18.7
Orbicella annularis.....	35.6	6.1
Mæandra areolata	36.8	5.5
Favia fragum.....	37.05	3.8
Siderastrea radians.....	38.2	1.0

A temperature of 35.3°C. for 60 minutes or of 36.8°C. for 30 minutes kills all the acroporas, but produces no visible injury to the inshore corals, such as the nodular or massive *Porites* (aff. *P. lutea*), the branched *Porites andrewsi*, *Pavona frondifera*, and *Pavona decussata*, *Psammocora*, and *Leptastrea purpurea*. This temperature would injure *Pocillopora damicornis*, which, however, can survive 35° C. for an hour without injurious effects, but is killed by 30 minutes' exposure to 36.7° C. Large massive *Porites* (aff. *P. lutea*) appears to be the most resistant Samoan reef-coral, and is killed by 30 minutes' exposure to 37.5° C. It also is the most resistant to asphyxiation by mud, or dilution due to rains, and lives closest to the shore and nearest to the mouths of streams.

In 1917 Mayor (*19*) found that there is an apparent converse relation between the rate of oxygen consumption in reef-corals from Tortugas, Florida, and their ability to resist high temperature, those corals which are most readily killed by heat having the highest metabolism (rate of oxygen consumption), as determined by Winkler's method (table 8).

Also, if sea-water be supersaturated with carbon-dioxide gas, the toxic effect is in the same order as that of high temperature. That is to say, those corals which are readily killed by heat are also correspondingly easily killed by H_2CO_3. It seems possible that some undetermined acid may accumulate in the tissues, due to increased metabolism under the influence of heat, and thus poison the coral.

TABLE 9.

Name of coral.	Average of oxygen consumption in 3½ hours in c. c. at 760 mm. pressure.	Range in oxygen consumption in the various experiments.	Average consumption of oxygen per hour.	Area of living tissue of corals in square centimeters.	Weight of living substance in grams.	Volume of coral in c. c.	Specific gravity of coral.
Pocillopora damicornis.....	2.6	1.3 to 3.6	0.74	....	1.58	25	2.2
Acropora formosa.....	1.7	0.97 1.97	0.48	50	2.3	10	2
Massive Porites aff. P. lutea.	2.4	1.48 2.48	0.68	30.6	3.8	61	1.7
Branched Porites P. andrewsi	2.3	1.8 2.7	0.65	135	7.6	31	1.77

This supposed toxic effect of carbon dioxide is not due to its replacing some of the oxygen of the sea-water, for I find that corals are remarkably insensitive to a reduction in the oxygen-supply, all species except *Acropora muricata* living more than 11 hours in sea-water under an air-pump which took out 95 per cent or more of the oxygen; and even *Acropora muricata* can withstand 6 hours of this treatment.

From July 30 to August 3, 1918, experiments were carried out upon four common genera of Samoan corals from the Aua reef-flat, using Winkler's method, and showing the metabolism of 4 species of Samoan reef-corals, based on their oxygen-consumption method; 5 experiments of 3½ hours each were made on each coral upon 5 successive days, in the dark, in sea-water at 27° to 28° C., having 4.26 to 4.55 c. c. of oxygen per liter, the oxygen being estimated as at 760 mm. pressure and 0° C. During the experiments each coral was kept in a glass-stoppered bottle holding about a liter of sea-water. The weight of living substance was determined after dissolving the stony substance in 20 per cent nitric acid.

TABLE 10.

Name of coral.	Oxygen consumed.
Pocillopora damicornis.....	468*
Acropora formosa.....	208
Massive Porites, aff. P. lutea.....	179
Porites andrewsi (a branched species).....	85

**Acropora muricata* from Tortugas, Florida, consumes 479 c. c. of oxygen per kilogram per hour.

From this we derive table 10, showing the cubic centimeters of oxygen consumed each hour by each kilogram of living substance of the coral.

The relation between rate of oxygen consumption and ability to resist high temperature in these Samoan corals is shown in table 11. This table brings out the

anomalous result that *Pocillopora*, which has a higher rate of metabolism than *Acropora*, is nevertheless more resistant to high temperature. *Pocillopora* is also a widely distributed coral, being found close to shore and as far out on the reef-flat as its fragile stems will permit. Thus at first sight it seems to break the rule of a converse relation between resistance to heat and rate of metabolism shown so closely by the Florida corals. We find, however, that if *Pocillopora* be buried beneath the mud or subjected to CO_2, it is killed quite as quickly as is *Acropora*. If, however, we take a *Pocillopora* and an *Acropora* and sprinkle sand or mud upon them, we find that the *Pocillopora* readily frees itself from the smothering substance by means of its very efficient cilia, whereas the *Acropora* is by no means so successful. Thus *Pocillopora*, while easily smothered if virtually covered by mud, is able under normal conditions to free itself from this danger and can therefore live closer to shore than can *Acropora*. It seems possible also that the ability to resist high temperatures which characterized *Pocillopora* may be due to the current over its surface which is maintained by its cilia, thus driving stagnant CO_2-laden water from its stems. The living tissue of *Pocillopora* is also much thinner than *Acropora*, and for a given weight of living substance it exposes a greater surface area to aeration.

TABLE II.

Name of coral.	Constant temperature, exposure to which for 30 minutes causes death.	Relative rate of oxygen consumption per gram of living substance in each coral at 27° to 28° C.
Pocillopora damicornis.....	36.7	5.5
Acropora formosa.....	34.4	2.4
Massive Porites aff. P. lutea....	37.5	2
Porites andrewsi.....	37.2	1

In 1917, I was led to suspect from experiments carried out upon corals of Tortugas, Florida, that death from high temperature might be due to the accumulation of acid, possibly H_2CO_3, in the tissues, the high rate of metabolism producing CO_2 at so great a rate that it could not be effectively gotten rid of by diffusion into the surrounding sea-water and thus it accumulated in the tissues and produced acidosis. If this hypothesis be true, an increase in the concentration of the hydrogen ion in the sea-water ought to be correlated with a lowered resistance to high temperature. I found that if 6 drops of hydrochloric acid be added to 1,500 c. c. of Samoan sea-water, the PH changed from 8.2 to 6.95, thus being nearly neutral at 27° C. Reef-corals survive in this water for at least 24 hours at 27° C. without apparent injury. Two jars, each holding 1,500 c. c. of sea-water of 4.48 c. c. of oxygen per liter and 8.22 PH, were kept in a thermostat chamber until their temperature was 36.6° to 36.8° C. Then 5 drops of HCl made the sea-water of one of the jars nearly neutral and of 6.95 PH. Two small pieces were then broken off from each coral, and one of these pieces was placed in the jar of normally alkaline sea-water and the other in the jar of neutral sea-water with results shown in table 12.

Thus the corals could withstand heat quite as well in sea-water made neutral by HCl as in normally alkaline sea-water. This experiment was tried a number of times, but the one cited above is typical for all the others, and there seems to be no definite relation between a coral's ability to resist high temperature and the alkalinity of the sea-water, provided the sea-water be not decidedly acid.

TABLE 12.

Name of coral.	Corals in normal sea-water of 8.22 PH.	Corals in neutral sea-water of 6.95 PH, made neutral by adding HCl to the sea-water.
Acropora formosa	Dead	Dead.
Pocillopora damicornis	Badly injured, probably killed	Badly injured.
Porites andrewsi	Injured but survived	Injured but survived.
Psammocora	Do.	Do.
Pavona frondifera	Apparently not injured	Apparently not injured.
Leptastrea purpurea	Do.	Do.

A more direct test of this matter was made at Tortugas, Florida, in May and June 1919, where many experiments were carried out by adding CO_2 to sea-water until its PH was reduced to 6.75, this being practically neutral at the temperatures of the experiments. The CO_2 was introduced by saturating 200 c. c. of the sea-water with carbon-dioxide gas under heavy pressure, and then adding this saturated water to 400 c. c. of natural sea-water of about 8.2 PH. Then, after heating this 4,200 c. c. of sea-water in a thermostat for from 12 to 15 hours, the average PH became 6.75, ranging in the various experiments from 6.65 to 6.9. The results are shown in table 13. In column 1 the temperature given was just sufficient to kill the coral after exposure for 1 hour in sea-water made neutral (6.75 PH) by the addition of CO_2. In column 2 the temperature given was just sufficient to kill the coral after exposure to it for one hour in natural sea-water of about 8.2 PH.

TABLE 13.

Name of coral.	No. 1.	No. 2.
	° C.	° C.
Acropora muricata	34.8	34.7
Porites astræoides	35.8	35.8
Porites clavaria	35.7	36.4
Mæandia areolata	36.2	36.8
Favia fragum	36.2	37.05

This experiment seems to show that the corals withstand heat nearly if not quite as well in sea-water made neutral by CO_2 as they do in natural alkaline sea-water.

We know, however, from the work of Henze (*20*) on sea-anemones that these cœlenterates have a wide range of adaptability, and when placed in sea-water with reduced oxygen their metabolism is also reduced and they survive the adverse condition without apparent injury. It seemed possible, therefore, that the presence of CO_2 in the surrounding water may have reduced the rate of metabolism of the corals, enabling them to resist an increase in temperature.

In order to test this, the metabolism of Samoan corals in normal sea-water at normal temperature was compared with their rate of metabolism in sea-water of the same temperature but rendered decidedly acid by the addition of CO_2. The

metabolism was estimated by determining the amount of oxygen consumed by the corals, using Winkler's method. Sea-water of 8.24 PH was made acid, and of 5.85 PH by running CO_2 into it. Two tightly stoppered glass bottles, each of 1 liter capacity, were used in the experiment and the temperature of the water was made 27.7° C., practically the same in each by placing them in a thermostat for 12 hours before the experiment. Experiments were made upon small pieces of *Pocillopora damicornis* and *Porites andrewsi*, the corals being kept for 2 hours in the bottles.

In the case of *Porites andrewsi*, the average oxygen-content in the normal sea-water was 4.48 c. c. of oxygen per liter, at 8.24 PH and 27.7° C., and the coral consumed the oxygen at the average rate of 0.31 c. c. per hour. When placed in sea-water of 4.85 PH, made acid by CO_2 and containing 3.5 c. c. of oxygen per liter, it consumed 0.24 c. c.; now 4.48 : 3.50 = 0.307 : 0.24, this being so close to 0.31 : 0.24 as to be practically identical. Thus no toxic effect appeared to be produced by the CO_2 and the coral simply consumed oxygen in proportion to the concentration of oxygen in the surrounding water.

Eight experiments upon *Pocillopora damicornis* gave a similar result. Thus the normal sea-water of 8.24 PH had an average oxygen-content of 4.1 c. c. per liter and the coral consumed on an average 0.215 c. c. of oxygen per hour. When placed in acid sea-water containing CO_2 and of 5.85 PH which had an average oxygen-content of 3.1 c. c. per liter, the coral consumed on the average 0.165 c. c. of oxygen per liter. Now, 4.1 : 3.1 = 0.215 : 0.165. In other words, the coral consumed oxygen at a rate proportional to the oxygen concentration in the surrounding sea-water, and showed no injurious effect from the decidedly acid sea-water in which it was placed.

The animal substance of the *Pocillopora damicornis* used in these experiments was removed from the skeleton by 15 per cent nitric acid and weighed; and this showed that it consumed oxygen in normal sea-water at 27.7° C. at the rate of 400 c. c. of oxygen per hour for each 1,000 grams of living substance of the coral.

These experiments made it evident that the slight changes in the concentration of CO_2 normally occurring in the water of reef regions can have no injurious effect upon the corals. Samoan corals are not obliged to withstand low temperatures, but the limits of coral-growth appear to be somewhat lower in this respect than has hitherto been suspected. Thus, at Boca Grande, west of Key West, Florida, on January 8, 1919, at 7^h45^m a. m., after four days of a severe "norther," the water over the flats became 15.8° C. (60.4° F.) for a few hours; yet corals such as *Mæandra areolata*, *Porites furcata*, and *Siderastrea radians* thrive on these flats, and were apparently uninjured by this temporary exposure to so low a temperature.

Experiments I made in Porto Rico indicated that reef-corals when cooled gradually become more and more inactive and lose their ability to capture prey if kept for half an hour at about 61° to 63° F., at which temperature the tentacles become temporarily incapable either of retaining copepods on their surface or of conveying attached prey to the mouth. Thus at these temperatures the corals would eventually die of starvation if from no other cause.

It was interesting to find that when the Aua Reef was impounded in sunshine during the lowest tide, it tended to become more alkaline in places and relatively more acid in others than the open ocean. Thus an alkalinity of 8.51 PH (0.31×10^{-8}) and water temperature of 32.1° C. was observed over the Aua reef-flat on March 24, 1917, the alkalinity of the water of the open ocean at this time being 8.25 PH (0.54×10^{-8}). There was a bacterial scum over the hot, stagnant water at this time. Again, at the low tide of July 16, 1920, the impounded water of the Aua reef-flat, 400 feet from shore, where the depth was about 5 inches, was of 8.6 PH at 27.4° C., and had 8.44 c. c. of oxygen per liter and a salinity of 34.79. At this time the water of the ocean outside of the reef was of 8.25 PH at 26.7° C. and had 4.67 c. c. of oxygen per liter, with a salinity of 34.7. Thus the reef-water was supersaturated with oxygen.

Experiments made at Tortugas, Florida, in 1917, showed that tide-pools, when cut off from the ocean at low tide and exposed to the sun, soon became supersaturated with oxygen and highly alkaline (8.65 PH), due to the photosynthetic activity of sea-weeds and of commensal algæ in the corals, and McClendon (*21*) had previously observed a diurnal range in the PH of the Tortugas lagoon due to photosynthesis, the water being more highly alkaline during the day than it is at night.

On the other hand, tide-pools, which lack plants and contain decomposing animal matter, accumulate CO_2 and become relatively acid, and some such cause may account for the local relative acidity, such as 8.01 PH, seen at one place when the Aua Reef was impounded at the low tide of March 23, 1917, the PH of the free ocean-water at this time being 8.23.

It will be recalled that Dana thought that reef-corals did not grow at depths of 20 or more fathoms, due to the low temperature of the water at these depths. Using a Negretti-Zambra reversing thermometer standardized by the Kew Observatory, I made a number of tests of the temperature at depths down to 33 fathoms off the seaward edges of the reefs of Tutuila and found that there is usually less than 1° C. difference in temperature between the surface and a depth of 200 feet. Thus, in a typical series taken September 7, 1919, east of Whale Rock, Pago Pago Harbor, Tutuila, in a place where the chart shows a depth of 213 to 222 feet, results are as given in table 14, the tide rising and the sea being roughened by a strong breeze; air 27.5° C.; time 3 p. m. It is evident that this slight decline in temperature could not be injurious to coral-reef growth.

TABLE 14.

Depth.	Temperature.
feet.	° *C.*
Surface	27.4
25	27.3
50	27.2
75	27.2
100	27.2
150	27
200	26.75

Wood Jones (*16*) and others have suggested that the deposition of silt over the coral-heads in the undisturbed water of the depths may be the cause of the decline in growth of coral. This is undoubtedly an important factor, but I find that in many places in Samoa, as over the Taema Bank, where the water is constantly agitated by the Pacific swell and the bottom is clean, hard, and free from silt, the corals at depths of 8.5 fathoms grow only to about one-third the linear dimensions

they attain in shallower water, and there are wide spaces between the heads, indicating unfavorable conditions. It looks as if some factor such as light may have a decided influence in determining the growth of coral. Indeed, Vaughan noticed that corals did not grow under the shade of a wharf at Tortugas, Florida, although they flourish on those piles of this wharf which are exposed to sunlight. I found that in going down in a diving-helmet to the moderate depth of 40 feet off one of the coral reefs of Pago Pago Harbor, the light became so reduced that one could not see objects clearly which were more than 4 feet away. No *Acropora* was found in this region, but *Pocillopora*, *Psammocora*, and *Porites* and some others were able to grow.

While in Samoa we observed some of the vicissitudes to which coral-reefs may be subjected. Thus on May 21, 1920, there was an exceptionally low tide, while the ocean was flat, calm, and a heavy rain fell for several hours. In the absence of the usual surge, the lithothamnium ridge of the coral-reef was continually drenched by the rain, and thousands of *Acropora leptocyanthus* were killed, but the other species of *Acropora*, such as *A. hyacinthus*, and the lithothamnium itself, survived the deluge of fresh water without apparent injury.

Again, at about 11 p. m. of June 28, 1920, a torrential rain commenced at Pago Pago and about 14.2 inches had fallen by 8 a. m. This rain continued with but little interruption until July 1, by which time 37.5 inches had fallen in 4 consecutive days,[1] this being the highest rainfall for so short a period yet observed in Tutuila, according to the record compiled by Lieutenant F. C. Nyland. The harbor-water became so muddy that objects 2 inches below the surface could not be seen. At 10 a. m. on June 29, 45.6 liters of water were gathered from the mid-region of the reef-flat off Morr's wharf, Pago Pago Harbor, and it was found that it contained 3.67 grams of mud per 100 liters, or practically 1 ounce avoirdupois of mud per cubic yard. This mud was dark brown in color and consisted of finely divided particles and, on boiling it in HCl, 50 per cent of it dissolved, leaving a very dark brown volcanic residue. Thus about half the mud in suspension over the reef-flat was derived from the volcanic slopes of the island and half by agitation from the surface of the reef-flat. In this region there was a sparse growth of corals, such as *Acropora hyacinthus*, *A. leptocyathus*, several species of branched *Acropora*, *Pocillopora damicornis*, and *Porites*, but all were killed by the mud and dilution. The dilution at times during the shower amounted to fully 50 per cent on the surface. Thus off Blacklock's Wharf, where the normal salinity was about 33 to 34, the salinity of the surface was found to be 17.97, and at a depth of 34 inches it was 26.56.

The mud was more fatal to *Acropora hyacinthus* than to *A. leptocyathus*. Thousands of stocks of *A. hyacinthus*, many of them 2 to 3 feet in diameter, were killed all around the shores of Tutuila to a depth of 10 feet below the surface, but the *A. leptocyathus* survived in most instances fairly well. It is interesting to see that the pure, drenching rain-water of May 21 was more fatal to *A. leptocyathus* than to *A. hyacinthus*. Off the mouth of Fagaalu brook many heads of the massive *Porites*, allied to *P. lutea*, which must have been at least 50 years old and 5 to 7 feet

[1] 5.3 inches on June 28; 16.5, on June 29; 12, on June 30; 3.7, July 1.

in diameter, were killed by the dilution and mud of June 29 to July 1, 1920. In fact, the reefs of Tutuila suffered a loss from which they can not recover for many years.

This muddy water remained more or less apparent for 10 days or more following the rain, but the salinity soon became practically normal. Thus the inner parts of the harbors of Fagasa, Aso, Massefau, Aofono, Aoa, and Vatia were very muddy on July 9 to 12, but the salinity of these muddy waters ranged from 33.89 to 34.43, whereas the clear ocean-water at the mouths of the harbors was 34.51 to 34.87.

When, as Dr. Alexander Agassiz's assistant in 1898, I first saw the barrier reef off the mouth of Suva Harbor, Fiji, it was remarkably rich not only in corals, but in fishes and invertebrates; but in 1918 this reef had been largely killed by mud from the harbor and from the Rewa River delta, and by 1920 it had suffered even more apparently by sewage from the growing town of Suva. Of the large number of *Alcyonaria* and corals of this reef which Professor L. R. Cary and myself had weighed, measured, and photographed in 1918, none had made anything like a normal growth by 1920 and many of them were dead. In fact, every alcyonaria we experimented upon had shrunken in size. Moreover, the corals growing naturally over wide areas of reef near Suva had died between 1918 and 1920, some very rich reefs being converted into very poor ones. Thus it appears that the growth of a coral-reef is probably not a uniform process, but is subject to vicissitudes and times of check as well as to periods of rapid development.

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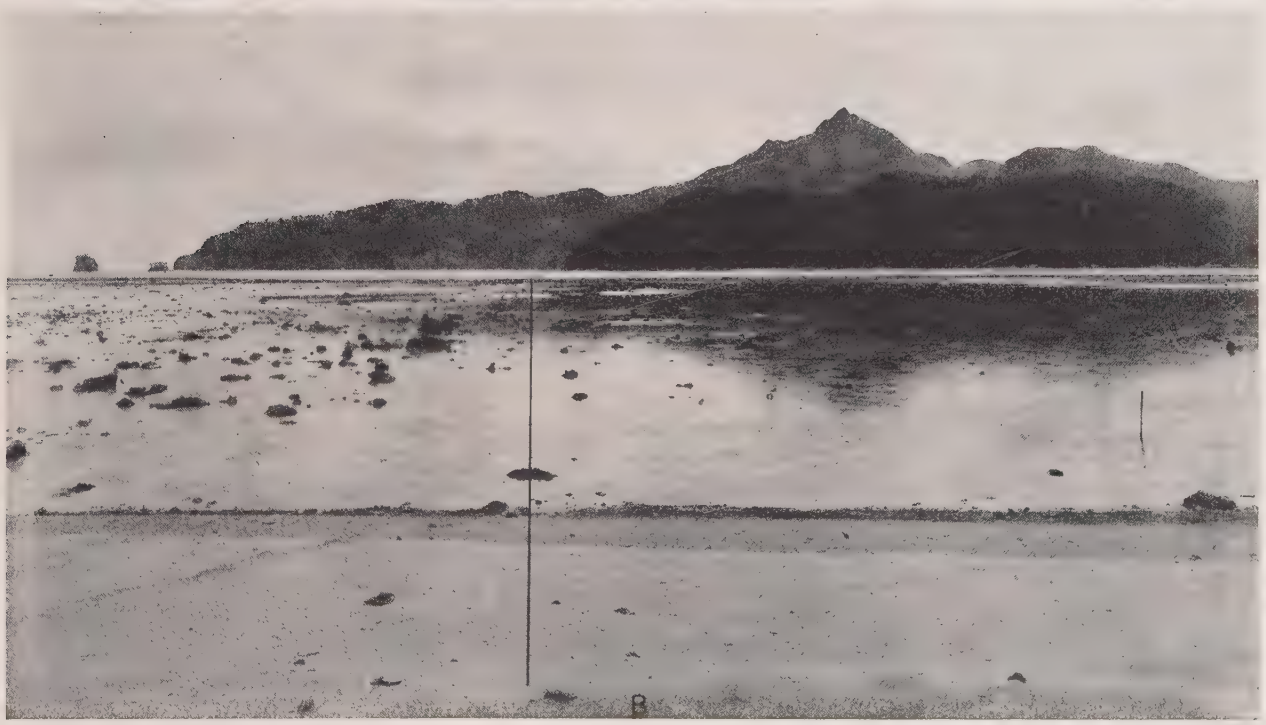
Pago Pago Harbor showing the Aua Line, stations at which corals were grown, and depths of borings through the reefs at Utelei and Aua.



A.—Storm-tossed coral block at seaward edge of the Aua Line, showing the lithothamnium ridge and stocks of *Acropora leptocyathus* laid bare at low spring tide.
B.—View across the Aua Line at low tide. Line drawn across reef-flat marks position of the Aua Line.

A.—Branched *Acropora* laid bare at low spring-tide on the Aua Line shoreward of the lithothamnium ridge, which is barely uncovered.

B.—Seaward edge of the Aua Reef near outer end of the Aua Line, showing *Acropora leptocyathus* and lithothamnium.

A.—The Aua reef-flat at low tide.
B.—The Aua reef-flat from the summit of Papatele. The small dark object near the middle of the reef-flat is the derrick used in boring through the reef in July 1920. The boring was 156 feet deep and ran into hard basalt at the bottom.

A.—Emerged platform of marine erosion at base of 300-foot cliff at Round Point, South Shore of Tutuila.

B.—Emerged platform of marine plantation at base of cliff on east side of Annu Island, off Tutuila.

A.—Emerged platform at base of the sea-cliffs of Foisina Island, seen from Ofu Island, Manua group, Samoa.

B.—Emerged platform of marine erosion at base of a sea-cliff on the north shore of Tau Island, Manua group, Samoa.

CAUSES WHICH PRODUCE STABLE CONDITIONS IN THE DEPTH OF THE FLOORS OF PACIFIC FRINGING REEF-FLATS.

By Alfred Goldsborough Mayor.

As is well known, in 1890 Sir John Murray (*1*)[1] concluded that the lagoons of barrier reefs and atolls may have been excavated by submarine solution of limestone. Alexander Agassiz, (*2*) and also in many papers upon the reefs of the Atlantic and Pacific published by the Museum of Comparative Zoology at Harvard College between 1893 and 1906, held the same idea, but in addition he maintained that scouring due to currents and agitation caused by waves was a factor even more potent than solution in the excavation and maintenance of lagoons. The remarkably uniform depth of 20 to 25 fathoms which characterize Pacific atoll lagoons was due, according to Agassiz, to the absence of wave-currents or agitation below this depth, and the fact that even the greatest ocean-waves produce no appreciable apicycloidal movement of water particles at depths greater than 120 feet has been sustained by theoretical considerations of wave-motion as well as by the observation of naval divers. Thus modified by Agassiz, the Murray solution theory became for a time a prominent competitor of Darwin's theory of subsidence as an explanation for the production of atoll and barrier-reef lagoons.

Thus Guppy, (*3*) who studied the Solomon Islands, and Bourne, (*4*) who describes the Chagos group and Diego Garcia, conclude that the barrier reefs and atolls of these regions are not due to subsidence, but they also maintain that at present these lagoons are either filling up with silt which is being washed into them or are in a balanced state, the solution of limestone by the sea-water being offset by the growth of coral and by precipitation of calcium carbonate.

Bonney (*5*) maintained that while submarine solution of limestone was known to be considerable at depths greater than 2,000 fathoms, there was no evidence of its being an important factor in shallow water, and the objection was also raised by many authors that if solution was capable of dissolving out lagoons to a depth of about 20 fathoms, why did it so suddenly become ineffective below that depth.

Every student of coral-reefs seems to have agreed that at least some submarine solution of limestone takes place in shallow water until Drew (*6*) found that a bacillus, *Pseudomanas calcis*, is precipitating $CaCO_3$ in the water of the Florida-West Indian region, and later McClendon's (*7*) analysis of Tortugas sea-water caused him to conclude that the water of Tortugas, Florida, is supersaturated with calcium and therefore can not dissolve calcium carbonate. In fact, as Dall and Vaughan

[1] The serial numbers in parentheses refer to Literature Cited.

showed, calcium is being precipitated in the sea-water of the Florida-Bahama region, but McClendon doubts whether Drew's bacillus is the chief agent in causing this precipitation. Lipman, (*8*) who studied the bacteria of the sea-water of Samoa, also decides that Drew's bacillus is a negligible factor in producing precipitation of calcium carbonate. As we will show, the sea-water of Samoa is supersaturated with calcium, as is that of Tortugas. Vaughan, (*9*) in his geologic and ecological study of the reefs of the Florida-Bahama region, also maintains that no appreciable solution of limestone takes place in shallow water such as reef-corals grow in; and Mayor (*10*) found that mollusk shells which had remained immersed in stagnant Tortugas sea-water for a year lost no appreciable weight. It thus appears that the solution of calcium carbonate in tropical sea-water is so slight as to be negligible, but the question remained open as to whether in regions of shallow flats, where the sea-water is often diluted by rains or by streams, limestone might not be dissolved. It seemed possible that this might have been a factor tending to deepen and widen the lagoons of volcanic islands surrounded by barrier reefs.

It is, indeed, quite apparent that fringing reefs disintegrate and disappear to some extent over their shoreward parts as they advance seaward, and if this process were to continue unchecked, the original fringing reef would be converted into a barrier reef, with a deep lagoon along the shore; but this process does appear to be checked, for I know of no intergrades between fringing reefs and barrier reefs. Every Pacific reef I have seen surrounding an island is either the one or the other.[1]

In the Pacific, in places exposed to breakers, lithothamnium forms a smooth veneer over the seaward parts of the reef, across which the surges glide without finding any obstacle upon which to exert their force; and thus the highest part of the reef is in the region of the breakers, this being 6 inches or more above water at the lowest spring tides. We see that this veneer of corallines and lithothamnium not only binds all elements of the reef together, but above all prevents the waves from getting an effective "grip" upon the reef, and thus protects it from destruction by the sea.

Back of the lithothamnium ridge, the reef-flat is submerged at all tides, and yet as the reef grew outward from the shore its advancing edge of lithothamnium must have been constantly above low-tide level. It is evident, therefore, as was observed by Darwin (1842, p. 16), that limestone disappears to some extent back of the lithothamnium ridge as the reef grows outward. Indeed, the lithothamnium of the shoreward parts of this ridge itself, away from the dash of the breakers, can be seen to be dying and disintegrating, for as was long ago observed by Darwin and Dana, it thrives well only where the waves surge in full force or it is surrounded by pure ocean-water, as on the submerged seaward precipices of the reef.

Thus every Pacific fringing reef upon which the breakers dash, and which has a lithothamnium ridge along its seaward edge, has a shallow lagoon between this lithothamnium ridge and the shore; although this "lagoon" is usually so shallow

[1] Darwin (*Structure and Distribution of Coral Reefs*, 1842, p. 102; 1898, p. 138) recognizes that if his theory be true reefs intermediate in character between fringing and barrier reefs should be found, but he is apparently able to cite only one instance—the reef on the southwest coast of Madagascar—and he himself casts doubt upon this example, which indeed appears to be a barrier reef with its lagoon partially filled with mud.

that it is completely drained and its bottom laid bare at the lowest spring tides. The bottom of the shallow lagoon of the reef-flat consists of loose fragments of all sorts of dead or alive limestone-making organisms, and were it not for the protection afforded by the lithothamnium ridge it would be churned into fine particles and considerably deepened by the waves and currents. Writers have not laid sufficient stress upon this fact, nor did I realize it until upon returning to Samoa after a year's absence it was seen that practically every rock and coral-head on the floor of the reef-flat inside of the lithothamnium ridge had been moved several feet or more from its former situation. Yet there was only one strong gale during the year, and the only unusual disturbance appears to have been due to the earthquake wave on the night of June 25, 1917, when the harbor-water suddenly sank about 3 feet above high tide, oscillating several times with decreasing amplitude, and it may also be of interest to state that the Tongan earthquake of April 30, 1919, produced quite similar oscillations of sea-level in Pago Pago Harbor. Native traditions state that about 50 years ago a wave fully 20 feet high surged into Pago Pago.

One may assert that every coral-head and rock of the reef-flat of Pacific fringing reefs is *loose*, no matter whether it is a mere fragment or a mass of several tons in weight, and in time of storm the grinding together of these movable fragments tends finally to reduce them to sand, which is either cast ashore, washed off the reef-flat by currents, or dissolved in the intestines of holothurians.

Mayor, (*11*) from a study of the fringing reef around Murray Island, Torres Straits, was led to conclude that possibly rain and stream water discharged over the flat from the volcanic shore might be capable of dissolving limestone, thus causing the floor of the reef-flat to be depressed below the level of the lithothamnium ridge. It was observed that fragments broken from the lithothamnium ridge became smaller and more cavernated as they were driven shoreward, those near the beach being highly cavernated and evidently disintegrating.

In order to determine the rate of this disintegration, 23 fragments of reef limestone incrusted with lithothamnium and evidently derived from the lithothamnium ridge were gathered on August 11, 1919, from the middle of the reef-flat off the village of Aua, Samoa, and after being marked with numbered brass tags, weighed, and their cubic contents determined, they were replaced upon the reef-flat. These rocks were recovered, remeasured, and weighed on May 19, 1920, after having remained for 9 months in water about 10 inches deep at low tide and 150 to 200 feet from shore in a place where the currents over the reef-flat flowed with average force. The disintegration of these rocks may be appreciated by inspecting the figures of plate IX. They were of very irregular shape, the largest being 346 by 322 by 104 mm. and weighing 6,637 grams, while the smallest was 1,644 by 75 by 59 mm. and weighed 581 grams.

On May 19, 1920, after having remained submerged upon the reef-flat for 9 months, it was found that all but one of these rocks had lost weight, the exception being a rock upon which there was a vigorous growth of bryozoa, and a small *Pocillopora*.

To give an idea of this loss of weight, in 1919 the average rock weighed 2,230 grams (about 4.9 pounds avoirdupois) and its volume was 1,180 c. c., while after

remaining upon the reef-flat for 9 months this average rock weighed only 2,115 grams and its volume had become reduced to 1,119 c. c.

It had therefore lost 115 grams or 61 c. c., and this would make it seem that this average rock of 4.9 pounds in weight would be wholly disintegrated and disappear in 14 years and 6 months. On an average, the rocks were losing in height at the rate of about 2 mm. per annum, and most of their loss was due to cavernation rather than to surface reduction. We must not conclude, however, that this very rapid disappearance of limestone is due to solution, for these rocks were filled with boring algæ which left a thick, felt-like mass after the rock itself had been dissolved in nitric or hydrochloric acid. Not only were these algæ dissolving the limestone, but mollusks, worms, and sponges cavernated it, and echini and holothurians contributed to its disintegration; and the particles of calcareous sand or mud resulting from these destructive agencies would be removed from the reef-flat by currents in time of storm, either being washed over the deep northern edge or thrown ashore to constitute beach sand. In fact, as we will later show, we have good reason for the belief that the disintegration and disappearance of limestone over reef-flats is due not to solution by sea-water, but to causes such as the effects of currents and of organisms which break the stone up into particles small enough to be transported by currents, or, as in the case of boring algæ, sponges and certain mollusks dissolve the stone by acid.

The currents over the reef-flat prevent the accumulation of sand and mud upon its floor, and, realizing their importance, I made use of an Ekman meter to study the currents over the fringing reef off Aua Village, Pago Pago Harbor.

When the wave-fronts advance over the open sea to the shallow water of the edge of the reef, they are at once deflected in direction in such manner that the wave-front is made to trend parallel to the direction of the seaward edge of the reef-flat and the waves then advance inward over the reef-flat perpendicular to the trend of the reef-edge. This is well shown in a photograph of the reef-flat off Faleasau Village, Tau Island, kindly given to the author by Mr. Nicholas Knechtler, and here reproduced as plate X. It will be seen that the wave-fronts which are coming in over the deep sea at a wide angle to the trend of the seaward edge of the reef are at once deflected when they strike the reef-flat so as to trend in the direction of the reef-edge.

Thus every wave hurls water straight up on the slope of the lithothamnium ridge, and backs it up over the reef-flat. As the intervals between waves are, however, longer than that of the upward rush of each breaker, the water is for the greater part of the time flowing back down the slope of the lithothamnium ridge into the sea, and this current is only interrupted for a short time during the surge of each breaker up over the slope (text-fig. 1). Thus one always meets with a decided surface current setting to seaward from the outer edge of every breaker-washed fringing reef, and often this outflow is so strong that one can not swim from the open sea to the reef edge. In fact, on one occasion the author nearly lost his life in such an attempt. We see, then, that whatever their direction, the waves tend to throw water up upon the reef-flat.

Under the influence of the usual trade-wind, the inward rush of water dies out about 250 to 300 feet shoreward from the reef edge, and in this region there is no appreciable current, the water simply being backed up into a sort of aqueous ridge. Naturally, this heaped-up water must escape, and all of it can not escape against the periodic rush of the breakers, so it constitutes a steady current flowing over the reef-flat parallel with the trend of the beach and escaping to the sea through any deep channel in the floor of the reef-flat. The direction of this current is determined by the trend of the shore and by the wind, and a reversal in the wind will finally cause it to go in the opposite direction along the shore. In tropical regions, however, the trade-wind is not often reversed in direction, and so the current is for the greater part of the time constant in direction.

Many observations were made of the currents on the reef-flat off Aua Village, Pago Pago Harbor, and the results of a typical set of observations made between August 7 and 27 is shown in table 15.

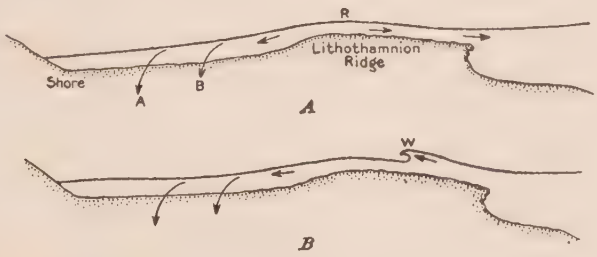


FIG. 1.

From August 4 to 11 the Ekman meter was placed at about the middle of the reef-flat, on the so-called "Aua Line," over which corals were counted, and most of the observations of this reef-flat were made. On August 13 to 27, however, the meter was placed about 150 feet from shore, near the northern edge of the reef-flat. The currents over the two stations were, however, practically identical in rate and direction. This current commonly flows northward, parallel with the trend of the beach, and pours out into deep water over the northern edge of the reef-flat. Its northerly trend is due to the trade-wind which blows in from the southeast; on August 7, however, the wind reversed and blew toward the south, and this finally caused the current to move southward; but for a time the current retained its northern direction over the bottom after it had been forced southward over the surface. The fans of the propeller of the Ekman meter were placed 7 inches above the bottom. The rate of the current was relatively independent of the height of the tide until as the tide fell the crest of the lithothamnium ridge began to appear above water and the current became reduced; but the wind was the dominant factor in determining the rate and direction of the current, the force of the breakers over the seaward edge of the reef being also an essential factor. Under normal conditions of trade-wind and a fairly high tide, the current ranged from about 15 to 20 feet per minute, and no sand was transported over the bottom. When the current became 42.5 feet per minute (21.6 cm. per second), a few light, flat grains of sand derived from dead and decomposed *Halimeda* were

TABLE 15.—*Rate of current which normally flows northward parallel with shore over reef-flat off Aua Village, Pago Pago Harbor, Samoa.*

Date, 1919, and station.	Time of observation.	Wind.	Sea.	Height of tide in inches.	Rise or fall of tide in inches.	Rate of current.		Remarks.
						Cm. per sec.	Ft. per min.	
Aug. 4. Station 450 feet from shore on the "Aua line" of reef-flat.	10h30m to 11h a. m. 11 05 11 35 a. m. 11 38 12 08 p. m. 1 20 1 50 p. m. 1 53 2 23 p. m. 2 25 2 55 p. m. 2 57 3 27 p. m. 3 28 4 04 p. m. 4 05 4 35 p. m. 4 36 5 06 p. m.	Light breeze to NE.	Breakers moderate, below average.	25.25 at 10h30m a.m. 29 at 1h50m p. m. 17.5 at 5h06m p. m.	2.5 rise 2 rise 2 rise 1 rise 0.5 fall 1.5 fall 2.5 fall 2.5 fall 2.5 fall 2.5 fall	11 7 7 6.9 7 6.7 7.5 7.7 8.8 9.2	21.6 13.8 13.8 13.5 13.8 13 14.8 15 17.3 18.2	Neap tide, wind and sea below average.
Aug. 5.	9h18m to 9h48m a. m. 9 49 10 19 a. m. 10 20 10 50 a. m. 10 51 11 21 a. m. 11 22 11 52 a. m. 11 53 12 23 p. m. 12 26 12 56 p. m. 12 57 1 27 p. m. 1 59 2 29 p. m. 2 30 3 00 p. m. 3 01 3 31 p. m. 3 34 4 04 p. m. 4 05 4 35 p. m. 4 36 5 06 p. m.	Very light breeze to NW., wind set at S. at 11h30m a. m. strong wind to S., breeze lessened, strong again to S.,nearly calm, light breeze to ENE.	Sea less active than on Aug. 4.	13.5 at 9h18m a. m. High and 31.5 at 2h29m p. m. 23 at 5h06m p. m.	3 rise 1.5 rise 3.5 rise 2 rise 2 rise 0.5 rise 4.0 rise 0.5 rise 1 rise 0 rise 1 fall 2 fall 0.75 fall 2.25 fall	5.75 4.28 4.75 6.27 6.34 1.06 3.8 1.3 2.45 2.7 1.4 1.03 3.4 3.9	11.2 8.4 9.35 12.3 12.5 2.09 7.5 2.6 4.8 5.25 2.7 2.03 6.6 8.8	Moderate wind blew against current nearly all day but did not reverse current, which continued to flow in its normal direction toward north.
Aug. 7.	9h22m to 9h52m a. m. 9 53 10 33 a. m. 10 33 11 03 a. m. 1 57 2 27 p. m. 2 27 2 57 p. m. 3 3 30 p. m. 3 37 4 07 p. m.	Light breeze to the south.	Ocean flat.	11.25 low at 9h52m a. m. 34.5 high at 4h07m p. m.	0.5 fall 1.75 rise 0.75 rise 18.25 rise 0.5 rise 2 rise 0 rise	2.05 0.9 1.4 1.3 to S. 0 0 0	4.03 1.77 2.75 2.4 to S. 0 0 0	Current to S. on surface but to N. on bottom; current completely reverse by wind.
Aug. 9	9h22m to 1h37m p. m. 1 38 2 08 p. m. 2 09 2 39 p. m. 2 04 3 10 p. m. 3 20 4 20 p. m.	Normal trade-wind to NE.	Breakers below average strength.	17 to 21 fell and then rose 37 at 4h20m p. m.	..... 3 rise 5 rise 3 rise 5 rise	11.7 9.1 8.5 3.7 5.3	23 17.9 16.7 7.28 10.4	
Aug. 11.	10h40m to 11h10m a. m. 11 12 11 42 a. m. 11 43 12 21 p. m. 12 22 1 47 p. m. 1 55 2 55 p. m. 2 56 3 26 p. m. 3 28 3 58 p. m. 3 59 p. m. 3 59 4 29 p. m. 4 30 5 00 p. m.	Normal trade-wind to NE.	Breakers normal. Stronger than on Aug. 9.	15.5 at 10h40m a. m. 0.5 low at 12h21m p. m.	3 fall 2 fall 1 rise ..... 3 rise 7.5 rise 4.5 rise 4.5 rise 6 rise 3.5 rise	15.25 13.9 12.9 ..... 5.8 12.2 11.9 10.8 12.1 11.6	30 27.3 25.4 ..... 11.4 24 23.4 21.25 23.8 22.8	Spring tide of full moon.
Aug. 13.	9h10m to 9h40m a. m. 9 41 11 16 a. m. 11 17 1 17 p. m. 1 18 1 48 p. m. 1 49 2 29 p. m. 2 30 3 30 p. m. 3 31 4 01 p..m. 4 02 4 22 p. m.	Strong breeze at about 30 miles an hour on the average.	Heavy breakers on the reef.	37.5 at 9h10m a. m. 9.75 at low 2h29m p. m. 22.5 at 4h22m p. m.	2.5 fall 14 fall 10.5 fall 0.75 fall 0 fall 3.75 rise 5.5 rise 3.5 rise	20 21.6 16.5 11.9 10.5 9.3 12.6 14	39.3 42.5 32.4 23.4 20.6 18.25 24.8 27.5	Strong wind and heavy swell No sand caught in net placed on floor of reef, except few grains of Halimida when current was 42.5 feet per minute.
Aug. 22.	9h38m to 10h18m a m 10 19 4 19 p m	Rain; gusty wind; fair surf.	Breakers and sea fairly heavy.	9 5–9.35 42.4 at 4h19m p. m.	0.15 fall 33 rise	10.8 8.65	21.25 17	Very high tide; near spring tide of Aug. 25. No sand displaced over bottom.
Aug. 27.	10h23m to 1h23m p m. (3 hours)	Strong gale from S. on night Aug. 26–27.	Very heavy breakers and driving spray. Surface of reef-flat rippled.	30–14	16 fall	30	59	114.5 grams of limestone. sand caught in net 15 ins. wide. Water over half flat clear.

transported, and when a wind of about 40 miles an hour caused the current to flow over the bottom at the rate of 59 feet per minute (30 cm. per second) and the surface was actively rippled, an appreciable amount of calcareous sand was dragged along the bottom, but the water still remained clear and transparent. (See table 15, Aug. 27.)

We see that a current of 60 feet per minute (0.68 mile per hour) begins to drag calcareous sand over the bottom of the reef-flat. This current is about the same as that required to transport siliceous sand over a smooth bottom, for this is usually stated to begin when the current runs at the rate of 0.68 mile per hour. The calcareous sand of the Aua Reef has a specific gravity of only about 1.89, and it tends to form in flat flakes which are easily transported by currents, and, moreover, the floor of the reef-flat is not smooth, but covered with rough, clinker-like masses of loose blocks of limestone constituting a surface which is readily scoured by currents.

We see that the currents over the floor of the flats of fringing reefs are primarily due to water heaped up over the reef-flat by the breakers, and thus the strength of the current is in some measure proportional to the ratio which this water heaped up by the breakers bears to the normal mass of water over the reef-flat. In other words, if the reef-flat were to deepen the current would be reduced in strength, and this probably accounts for the depth of 6 to 8 inches at ordinary low tide of the water over the flats of fringing reefs in the Pacific, the effective scouring action of the currents due to wind and breakers being limited to this shallow depth. In times of storm, the scouring action must be very effective, increasing as it does as the square of the velocity of the current.

In order to gain some conception of the amount of limestone sand lost to Aua reef-flat by being driven by currents off its northern edge, 6 barrels, the open mouths of which were each 2 feet in diameter, were weighted with volcanic rocks and sunk off the reef-flat close to the northern edge, so that the water was about a foot deep over their open tops at lowest tide. This test was continued from July 3 to August 4, 1918, during a period of normal weather in which only one gale occurred. The reef-flat at this point is about 1,200 feet wide, but sand spills over its northern edge along only about 800 feet of this length, the 400 outermost feet being subjected to the inward wash of the breakers. The innermost barrel was placed 100 feet from the shore, and the others at intervals of about 100 feet along the edge of the reef-flat. On an average each barrel caught 21.7 pounds of limestone sand during the month, nearly all of it resulting from a gale of about 10 hours with a wind velocity of about 40 miles per hour at its maximum. The sand was dehydrated in 95 per cent alcohol and dried in the sun before being weighed. By placing this sand in the water at the reef-edge and allowing it to drift over the barrels, it was found that the barrels caught only 12 per cent of the sand which was carried in the current over their open tops. Using these data, it would appear that about 1,000,000 pounds of sand (453,600 kg.) might be drifted off the Aua reef-flat in a year, but these figures are clearly too small, for more sand would be moved by the waves and current of a few hours of severe storm

than during months of ordinary weather, and such storms are quite frequent between February and April. In fact, the currents over the flats of Pacific fringing reefs suffice to keep the bottom free from any considerable accumulation of sand. In other words, when the rock is broken down into fine particles it is soon removed from the reef-flat, either being cast ashore or washed out into deep water.

However, assuming that 1,000,000 pounds of limestone was drifted off the Aua reef-flat each year, this would be equivalent to a deepening of the whole reef-flat by only 0.1 mm. per annum.

Holothurians (*Stichopus chloronotus*) are so numerous over the reef-flat between the chief's house of Aua and Breaker Point, Pago Pago Harbor, that there is on an average one of these animals for every 8.6 square feet of the floor of the reef-flat, or 290,000 individuals over the area in question. They are commonly filled with sand, which they swallow in large quantities, and, as has been suggested by Stanley Gardiner, Crozier, and others, they may exert an appreciable influence in deepening lagoons by dissolving calcareous sand in their intestines, especially as the occasional strong currents in such places would tend to remove the finer particles.

In this connection, Crozier (*12*) showed that in Bermuda, in certain areas frequented by *Stichopus mobii*, the amount of bottom material passing through the intestines of these animals is roughly 6 to 7 kilos (dry weight) per square meter of bottom per year. Crozier also decides that this holothurian fills its intestines with sand and discharges the contents at least twice, and probably three or more times, in each 24 hours, and as the gut of an average *Stichopus* of 270 mm. in length contains about 46 grams dry weight of bottom material, it might be expected to pass from 92 to 138 grams through its intestines each day. Thus, in Harrington Sound, Bermuda, the amount of bottom deposit passed through holothurians is perhaps 500 to 1,000 tons annually. Crozier also found that the yellow fluid in the stomach of an empty *Stichopus* is acid and of 5 to 6.5 Ph, and is thus capable of dissolving some calcium carbonate, but he does not estimate this amount, although he rightly states that the acidity of the stomach fluids is of the same order as that of rain-water. In order to evaluate the amount of limestone sand dissolved by holothurians, some experiments were conducted by me upon *Stichopus mobii* and *Holothuria mexicana* at Tortugas, Florida.

Calcareous sand, consisting chiefly of broken shells, coral, and fragments of *Halimeda* from the reef-flats frequented by this holothurian was first washed in fresh water to remove salt and very fine particles and then dried in the sun for 5 days or more, until upon repeated weighings the weight became constant. This sand was then placed in the bottom of a glass tank 68 cm. long by 30.5 cm. wide. Sea-water which was pumped up from the ocean through a hard-rubber pump was allowed to flow slowly through the tank containing the sand, the water over the sand being kept at a uniform depth of about 10 cm. Before the sea-water entered the tank it was filtered to prevent any further introduction of sand into the experimental tank. The waste water from the tank was made to flow into a large glass jar which served as a catchment basin to catch any sand that might flow out of the experimental tank. As a matter of fact, no sand was found in the catchment jars after the conclusion of the experiment.

In order to induce the holothurians to behave normally, the experimental tank must be placed out in the sunshine, and also removed from mechanical shocks, to which these animals are peculiarly sensitive. In fact, whenever one approached within a few feet of the tank, even though no shadow fell across the holothurian, the animal contracted. Moreover, the water of the tank must not be more than about 10 cm. deep, for otherwise the animals will crawl up upon the sides of the tank and will not feed normally. They will not behave normally in the diffused light of the laboratory, but must live in the intense sunlight and in pure ocean-water such as prevails over the shallow reef-flats which are their natural habitat.

I found that large holothurians such as *H. floridana* may defecate from 72 to 94 grams of sand (dry weight) per 24 hours. Also, when full of sand the fluid of their alimentary tract is usually about 7 PH, but when the animal is empty it becomes quite acid, ranging from 4.75 to 7 PH.

Owing to various accidents, I was able to carry out only two satisfactory experiments on the holothurians. A specimen of *Holothuria mexicana* 24.5 cm. long appeared to dissolve 16 grams of calcareous sand in 25 days, or at the rate of 234 grams per annum, and in another experiment a full-grown *Stichopus mobii* kept for 30 days in the tank appeared to have dissolved sand at the rate of 414 grams per annum. Taking the average as 324 grams per annum, and assuming that the Samoan holothurians do as well, it would seem that the 290,000 *Stichopus chloronotus* over the Aua reef-flat would destroy 208,800 pounds of sand per annum, and this would be equivalent to a deepening of the floor of the reef-flat by only 0.2 mm. per annum. The coral-heads growing upon the reef-flat would readily replace so slight a loss, despite the fact that not one-tenth of the area of the reef-flat is covered with coral-heads, for with the exception of the dense masses of *Acropora* which grow on the landward side of the lithothamnium ridge, the spaces between coral-heads are much greater than the area of the heads themselves. In fact, corals grow upon the surface of reef-flats much as plants do in the desert, with wide spaces between the stalks.

It appears, then, that the remarkably uniform depth of rather less than 6 inches at low tide which is so characteristic of Pacific reef-flats of fringing reefs between the lithothamnium ridge and the shore represents a balance between opposing factors. The dead coral and limestone blocks which so thickly bestrew the reef-flat disintegrate rapidly, due largely to the activity of boring algæ, while the living coral grows up to low-tide level and readily restores the loss. If, however, the growth of coral ever became so luxurious as to reduce the depth of the floor of the reef-flat to less than 6 inches, the currents due to breakers and wind would become more rapid, and as everything alive or dead lies loosely upon the reef-flat, the floor would become washed down to a balanced state at about 6 inches in depth. If, on the other hand, disintegration of material and poverty of coral-growth caused the floor of the reef-flat to become deeper than 6 inches, the current would decline in velocity and fragments washed in from the lithothamnium ridge would not be removed from the floor, so that new material would soon restore the depth to its balanced state of about 6 inches.

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Showing the corrosion of limestone rocks which lay submerged beneath sea water on the floor of the Aua reef flat, Pago Pago Harbor, Samoa. The Photographs illustrate disintegration between August 11, 1919, and May 18, 1920.

Reef-flat off Faleasau village, Tau Island.

INABILITY OF STREAM-WATER TO DISSOLVE SUBMARINE LIMESTONES.

By Alfred Goldsborough Mayor.

The highest part of the typical fringing reefs of the Pacific is close along the sea-front, where there is a ridge which projects about 6 inches above average low tide and is composed of dead coral veneered with living lithothamnium.[1] Between this lithothamnium ridge and the shore lies the reef proper, which is really a very shallow lagoon covered by water somewhat less than 6 inches deep at ordinary low tide, but often laid quite bare at the lowest spring tides. Thus, as the fringing reef has advanced seaward from the shore, its shoreward part has somehow become degraded, so that about a foot of limestone has been removed, the floor of the reef-flat being about a foot lower than the crest of the lithothamnium ridge.

Table 16.—*Rainfall record, U. S. Naval Station, Pago Pago, Tutuila, from 1900.*

Year.	Jan.	Feb.	Mar.	Apr.	May.	June.	July.	Aug.	Sept.	Oct.	Nov.	Dec.	Total.
1900	16.4	18.3	41.1	13.1	11.3	.1	4.5	3.0	5.9	9.8	19.6	24.1	167.2
1901	21.5	29.0	17.1	9.4	15.1	3.5	10.4	6.2	21.6	21.2	18.4	3.9	177.3
1902	12.9	37.9	5.2	14.2	5.7	25.2	3.0	4.4	5.0	8.7	11.0	14.4	147.6
1903	21.9	24.9	12.7	26.0	12.1	12.5	16.6	11.2	10.3	19.9	20.4	10.8	199.3
1904	21.2	27.2	10.5	21.3	8.3	11.0	10.5	13.1	10.9	9.3	21.9	10.9	176.1
1905	21.8	12.1	15.5	16.0	3.5	10.3	7.5	10.6	1.7	8.7	12.3	10.1	130.1
1906	5.3	9.9	18.0	14.1	18.6	14.7	6.1	7.4	12.7	13.2	14.2	13.0	147.2
1907	19.2	21.2	11.3	26.1	13.1	32.0	12.5	5.0	11.1	23.7	29.0	17.9	222.1
1908	32.6	48.3	39.5	13.7	23.8	9.2	8.2	10.4	28.5	16.1	41.7	12.4	284.4
1909	16.1	15.1	11.6	13.8	15.5	9.8	3.6	3.6	8.1	11.8	19.9	16.2	145.1
1910	20.7	10.2	28.1	19.7	9.5	16.3	3.4	11.6	17.8	15.1	15.2	30.9	198.5
1911	18.8	30.2	19.3	11.7	12.3	5.2	5.2	2.3	5.0	12.3	9.4	18.1	149.8
1912	15.1	7.7	22.3	31.9	30.8	12.1	4.5	3.5	14.7	10.4	20.0	22.4	195.4
1913	27.7	44.7	17.8	25.5	60.5	12.5	21.8	5.4	17.2	18.6	7.5	16.0	275.2
1914	4.0	20.4	14.7	18.1	9.4	19.5	10.7	20.4	48.9	49.2	16.1	19.2	250.6
1915	37.5	7.9	17.6	10.7	1.7	4.5	16.4	.6	10.0	10.1	8.7	30.6	156.3
1916	14.5	28.6	9.1	12.2	14.0	12.1	9.6	10.6	11.0	18.9	26.5	39.0	206.1
1917	38.3	34.6	34.0	22.2	5.4	20.7	7.5	5.8	7.8	19.5	29.8	24.3	249.9
1918	15.1	43.1	17.9	10.9	7.6	8.7	38.3	6.7	5.8	7.4	15.0	30.4	206.9
1919	49.8	22.6	16.5	8.4	14.8	9.6	2.0	4.7	11.3	3.9	16.9	14.4	174.9
1920	14.7	13.4	21.6	28.7	12.7	49.2	8.5	18.8	8.6	26.4	31.1	23.4	257.1

This limestone has, I believe, been removed by the action of currents over the reef-flat, which have removed particles of limestone resulting from the disintegration of the material constituting the floor of the reef-flat. This disintegration of limestone is caused by boring algæ, echini, boring mollusks, boring sponges, and worms, as well as by the attrition of moving water; and in addition the sand itself is to some degree dissolved in the intestines of holothurians, which swallow large quantities

[1] Darwin, 1842, *Structure and Distribution of Coral Reefs*, p. 10, was the first to describe this lithothamnium ridge at Keeling Atoll.

of it. It appears that solution of submarine limestone by sea-water, even when diluted by heavy rains or by fresh water discharged from the shore, is not a significant factor. This is quite in accord with the opinion of Vaughan, based upon his observations of Atlantic reefs, but it remained to establish this conclusion upon an experimental basis.

Tutuila, being purely volcanic and without elevated limestones, is an excellent island upon which to test the dissolving power of rain and stream water discharged from its shores over its fringing reefs. The island is densely forested from summit to shore, and it seemed possible that the rain-water with its acidity of about PH 5, due to CO_2, might become even more acid by percolation through decaying leaves and forest soil and might thus be able to dissolve the limestones of the reef-flats.

Moreover, the island has a heavy rainfall, as will appear from the official record of the rain-gage maintained at Pago Pago since January 1, 1900, by the U. S. Naval Station, an official report on which was kindly sent to the author by Lieutenant F. C. Nyland (C. E. C.), U. S. N., public works officer of American Samoa. This record from January 1, 1900, to December 31, 1920, is shown in table 16, which gives the average rainfall in inches and the range in monthly rainfall observed in 21 years.

TABLE 17.

Month.	Average rainfall.	Range in monthly rainfall.
	inches	*inches*
Jan.	21.3	4.0 to 49.8
Feb.	24.2	7.7 to 48.3
Mar.	19.1	5.2 to 41.1
Apr.	17.5	8.4 to 31.9
May	14.6	1.7 to 60.5
June	14.2	0.1 to 49.2
July	10.0	2.0 to 38.3
Aug.	7.8	0.6 to 20.4
Sept.	13.0	1.7 to 48.9
Oct.	15.9	3.9 to 49.2
Nov.	19.3	7.5 to 41.7
Dec.	19.1	3.9 to 39.0
	196.0	.....

January and February are months of maximum rainfall, while July and August are dry, but torrential showers may occur in any month, and indeed were these absent the rainfall would be only moderate. These torrential downpours give a very capricious aspect to the rainfall, and native traditions of periods of drought are doubtless true; thus, during the three months between June 1 and August 31, 1900, only 7.5 inches of rain fell, while by contrast the three months of January, February, and March 1917, gave 106.9 inches. To give an idea of the character of the torrential showers, 28.5 inches fell within 48 hours between June 28 and 30, 1920, about 14.2 inches falling during the night of June 28.

Such showers are ideal for eroding the slopes of the island, and after several months of heavy rain the steep hillsides become saturated with water and landslides are apt to occur, while an equal period of drought causes the thin soil to lose so much of its moisture that grasses, ferns, and the smaller plants wither, so that the aspect of the island becomes sere and yellow.

The probable error of the average annual rainfall of 196 inches for the 21 years from January 1, 1900, to December 31, 1920, is 6.8 inches. In other words, it is an even chance that the true annual rainfall lies between 189.2 and 202.8. It is evident that at times large volumes of water are suddenly poured out from the shores of the reef-flats.

In order to test the hydrogen-ion concentration of the water of Tutuila, use was made of a set of colorimetric tubes of phenolusulphonephthalein made by Hynson and Westcott of Baltimore, and ranging effectively from 6.6 to 8 PH. Also, a set of tubes of methyl red were used for PH below 6.6, and another set of colorimetric tubes of thymolsulphonephthalein made and kindly given to us by Professor J. F. McClendon were used for sea-water and ranged from 7.95 to 8.6 PH. I also used a Leeds and Northrop potentiometer for direct determinations of the hydrogen-ion concentration of waters and for standardizing the three sets of color tubes. The potentiometer was especially useful for testing acid rain-water and very alkaline sea-water. All bottles, beakers, and pipettes used in the tests were of "non sol" or Jena resistance glass, or of quartz; for ordinary glass is soluble in alkaline solutions and soon appreciably increases the alkalinity of the water.

According to Luther W. Cartwright, esq., secretary to the governor of Samoa, the average temperatures for each month for the two years 1918 and 1920 were as follows:

	°F.	°C.		°F.	°C.		°F.	°C.
Jan.	82.9	28.2	May	82.3	28	Sept.	80.8	27.1
Feb.	84	28.9	June	82	27.8	Oct.	81	27.2
Mar.	84.2	29	July	82.4	28	Nov.	83	28.3
Apr.	83.5	28.6	Aug.	81.4	27.4	Dec.	84.5	29.1

The highest temperature yet observed on Tutuila is about 90° F., and the[6] lowest 70° F.

These results are based upon observations taken every 4 hours throughout the 24 hours of the day, commencing at 8 a.m., and give an average annual temperature of 82.6° F. (28.1° C.). At a temperature of 28° C., water of about 6.9 PH or $0.126 \times 10^{-}$ hydrogen-ion concentration would be neutral.

On July 21–22, 1920, Professors L. R. Cary and W. H. Longley spent 24 hours on the summit of Mount Matafao, 2,133 feet above sea-level, and observed the thermometer every 2 hours, commencing at 11 a.m., while a similar set of observations was made by the author at sea-level at Pago Pago. The average temperature at the summit of Mount Matafao was 22.8°, while at sea-level it was 26.55°. Thus the average difference was 3.75° C. or 6.75° F., corresponding to a fall of about 3.2° F. per 1,000 feet in ascent on Tutuila.

It was found that the rain-water falling on Tutuila Island is acid, the range in hydrogen-ion concentration of 12 rains during March 1917 and August 1919 being from 0.126×10^{-5} to 1.0×10^{-5}. (See table 21.) Where they discharge into the sea the streams of Tutuila are, however, either neutral or slightly alkaline, and thus the fresh water which pours outward from the streams of the island can not dissolve limestone merely by reason of its acidity. Thus 26 tests of 11 streams and 6 springs at various parts of Tutuila, such as Pago Pago, Fagaalu, Massefau, Vatia, Laulii, Fagasa, and Leone, in March and April 1917 (see table 22), during the height of the rainy season, showed a hydrogen-ion concentration varying from 0.25×10^{-6} to 0.38×10^{-7}, the average being 7.10 PH, or 0.645×10^{-7}.

In March and April 1917, the ground was soaked by the torrential rains, which averaged more than an inch per day during the period of our visit, and thus the

streams and springs were swollen by surface seepage. In July and August 1918 and 1919, however, we were in the middle of the dry season; the island had suffered from several months of almost unbroken drought, and it was remarkable that the streams were less alkaline than they were during the wet season; but even so, no stream of Samoa which I was able to test was discharging acid water into the sea, although the springs were usually acid, due to CO_2.

Thus the spring at the crest of Vatia Pass was 5.75 PH on August 6, 1919, and 5.4 PH on July 20, 1920, by methyl-red test, but on boiling and then being cooled to 26.5° C., it showed 7.5 PH, indicating that its acidity was CO_2. The streams from these springs soon became alkaline after flowing over the ground, especially if they descended over waterfalls.

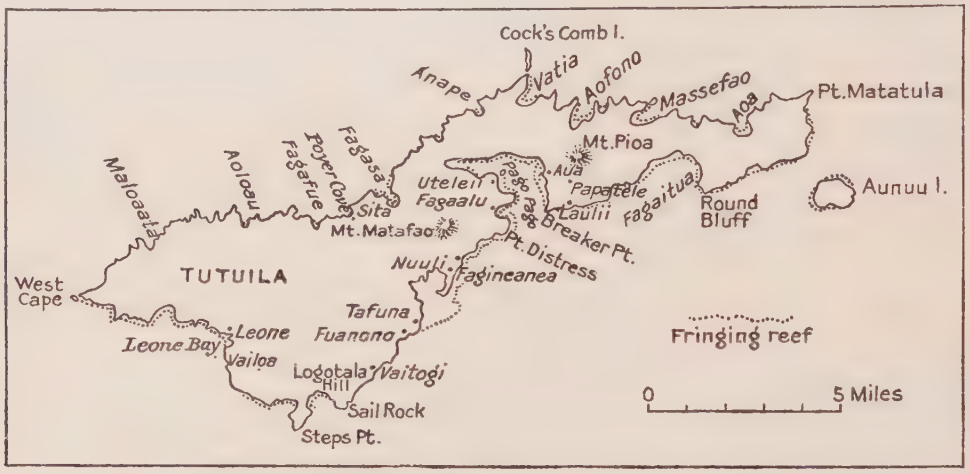


FIG. 1.

The streams of Tutuila have a somewhat "smoky" appearance, due doubtless to traces of organic matter, but their alkalinity, according to Professor Alexander H. Phillips, is due to bicarbonates of calcium, potassium, magnesium, and sodium. Thus, on April 14, 1917, a carboy of water was taken from the large stream which constitutes the waterfalls in Fagaalu Valley. The stream was then normal, being no longer flooded by the 4.3 inches of rain of April 12. Its temperature was 24.2° C. and hydrogen-ion concentration 0.5×10^{-7}. This water was analyzed by Professor Alexander H. Phillips, who reports as follows, June 11, 1917:

Analysis of water, in milligrams per liter, from Tutuila, Samoa; taken from Fagaalu stream above the cow-pasture and below the lower falls on April 14, 1917.

Color	None
Free ammonia	0.036
Albuminoid ammonia	.028
Nitrogen in nitrites	None
Nitrogen in nitrates	0.04
Oxygen consumed	2.05
Total solids	70.06
Silica (SiO_2)	26.55
Iron (Fe_2O_3), alumina (Al_2O_3)	.95

Total solids—continued.	
Calcium (Ca)	3.03
Magnesium (Mg)	2.20
Sodium (Na)	6.19
Potassium (K)	2.16
Bicarbonate (HCO_3)	9.60
Sulphate (SO_4)	4.06
Chlorine (Cl)	12.00
Nitrate (NO_3)	.17
Phosphate (P_2O_5)	.026

Most of the alkalinity is indicated by methyl orange, and very little by phenophthalein, and is thus due chiefly to bicarbonates. The chlorine is high, but this is to be expected from the proximity of the ocean.

Only the larger and more permanent springs were running on Tutuila in July and August 1918 and 1919, and all of these which were tested were acid, ranging from 5.75 PH to slightly below 6.6 PH. This acidity was due to carbon dioxide, and it disappeared on boiling, leaving the water strongly alkaline. Indeed, as the streams flowed toward the ocean their acidity steadily diminished, and a cataract of about 10 feet changed the water from acid to alkaline, so quickly did the CO_2 pass out of the running brooks to establish a balance with the atmospheric CO_2. This is illustrated by the large spring at the foot of the first waterfall, 792 feet above sea-level, in Fagaalu Valley, Tutuila.

On the morning of July 24, 1918, the drought still continuing, I again tested the Fagaalu Valley spring, and also followed the stream down to the large, deep pool at the foot of the fifth waterfall, about half a mile inland from the shore. This showed that the stream became more and more alkaline as it dashed over the successive cataracts, and its excess of carbon dioxide passed out into the atmosphere. These observations are presented in table 18, which shows hydrogen-ion concentration, PH, and temperature of the large spring 792 feet above sea-level in Fagaalu Valley, and of the stream which issues from it and dashes over four high waterfalls in its course to the sea, observed 10^h to $11^h 50^m$ a. m. July 24, 1918.

TABLE 18.

Station.	Hydrogen-ion concentration of water.	PH of water.	Temp., °C.
At spring 792 feet above sea-level	About 0.5×10^{-6}	6.3	24.3 in sunshine.
Stream 40 feet below spring, before it had passed over any waterfall	0.158×10^{-6}	6.8	23.2 in shade.
At foot waterfall about 10 feet high and 60 feet below the spring	0.71×10^{-7}	7.15	23.2 in shade.
At foot of second cataract	0.63×10^{-7}	7.2	23.2 in shade.
At foot of third and second waterfalls	About 0.5×10^{-7}	7.3	23.2
Pool at bottom of fifth waterfall, about 700 feet below the spring	0.5×10^{-7}	7.3	23.2

If an acid spring such as that at the stream-head in Fagaalu Valley were to pour directly into the sea it would tend to neutralize the alkalinity of the sea-water. In order to test the efficacy of this effect, I took measured volumes of the spring-water having a PH of about 6.5 and mixed this with sea-water of 8.19 PH, with the following results:

100 c. c. spring-water and 100 c. c. sea-water gave a mixture of 8.0 PH.
100 c. c. spring-water and 25 c. c. sea-water gave a mixture of 7.1 PH.
100 c. c. spring-water and 20 c. c. sea-water gave a mixture of 6.95 PH.
100 c. c. spring-water and 10 c. c. sea-water gave a mixture of 6.6 PH.

Thus 20 volumes of sea-water give a neutral solution if mixed with 100 volumes of Fagaalu spring-water at 25° C.

Tests were also made of streams and springs on Upolu Island, Samoa, with the results given in table 19, the temperature of these waters ranging from 23° to 28° C.

Here again we see that the springs were slightly acid, due to CO_2, but that as the streams flowed toward the ocean or the water was agitated in the air they became alkaline, due to loss of CO_2. The crater lake Lanutoo is, however, an exception, for its acidity is not due to CO_2, and the water contained so little chlorine that its acidity could not be due to HCl. I was, however, unable to test it for sulphides, but barium carbonate + HNO_3 gives no precipitate, thus showing that there was no large amount of SO_4 present.

TABLE 19.—*Alkalinity of streams and springs on Upolu Island, Samoa.*

Date (1918).	Name of stream or spring.	Locality from which water was taken.	PH of water.	Remarks.
Aug. 7....	Vaisigano stream.....	⅛ mile inland, in quick water..	7.4	Largest stream into Apia Harbor.
Aug. 7....	Fagalii stream.....	.....do	7.1	Stream east of Apia.
Aug. 7....	Letongo stream.....	.....do	7.1	Do.
Aug. 7....	Faluasou stream.....	About 4 miles inland, in the mountains.	7.3	Stream west of Apia.
Aug. 8....	.....do	.....do	7.15	Do.
Aug. 7....	Vailoa spring.....	West of Apia.....	6.7	On shaking in air at 28° C. this water became 7.3 PH; when boiled and then cooled to 28° C. it became 7.7 PH.
Aug. 7....	.....do	West of Apia, near Vailoa spring.	6.7	
July 6....	Pool at foot of Papaseea waterfall (upper fall).	In mountains of Upolu.....	7.55	
July 7.....	Small tributary to Mulivai stream.	About 0.5 mile inland.....	6.6	
July 7.....	.....do	In quick water near sea.....	7.3	
Aug. 8....	Mountain lake Lanutoo, which is in a tufa crater; has no apparent outlet.	About 2,400 feet above sea-level.	6.6	When boiled and then cooled to 27° it retained its PH of 6.6. Its acidity is not due to chlorides ($AgNO_3$ test) nor to CO_2.

Tests were also made of some streams of Viti Levu Island, Fiji Islands, as will appear from table 20.

Rewa River, the largest stream in Polynesia, is alkaline, as is also the Navua River, which flows over cataracts in the high mountains toward the south coast of Viti Levu, but the streams flowing into Suva Harbor are slightly acid, due to CO_2, although it takes 9 volumes of this stream-water mixed with 1 volume of sea-water to make a neutral solution. It is therefore improbable that this acidity is sufficient to enable them to dissolve submarine limestone. These streams in the neighborhood of Suva Harbor, Fiji, and the outlet of the crater swamp of Aunuu Island, Samoa, are the only acid waters I have as yet observed flowing into the sea in Polynesia.

It may be of interest to observe that the streams of Oahu, Hawaiian Islands, appear to be decidedly alkaline, due doubtless to the elevated limestones upon this island. Thus, on the clear, rainless day of April 25, 1917, Dr. C. Montague Cooke kindly took me in his motor-car to the important springs and streams near Honolulu, and these were all alkaline, ranging from 7.1 to 8.12 PH, the average

being 7.34, or 0.457×10^{-7}. These Hawaiian springs and streams were as follows:

	PH.
Spring at side of Pali road below reservoir No. 2	7.35
Stream issuing from reservoir No. 2	7.6
Nuanu stream at Loakaha, 800 feet above sea-level	7.1
Small stream on Kanaohe side of Pali, 1,000 feet high	7.5
Palolo Valley, main stream about 300 feet above sea-level	7.73
Manoa Valley, main stream	7.5
Moanalua Valley, stream just below the polo field	7.35
Punahou spring, Honolulu	8.12

The larger streams of Tutuila were at all times slightly alkaline, but the deep-seated springs are slightly acid, especially in the dry season, when surface seepage does not mingle with their waters. When swollen by surface drainage after heavy rains, the streams usually become less alkaline. Thus the large brook entering the harbor at Pago Pago Village, Samoa, had a normal PH of about 7.15, but the 7.8 inches of rain of March 19, 1917, reduced this to 6.97 PH. Similarly, the stream of Fagaalu Valley fell from about 7.35 to 6.97 PH, due to the same rain; but even so, these streams still remained alkaline.

TABLE 20.—*Alkalinity of streams and rivers of Viti Levu Island, Fiji Islands.*

Date (1918).	Name of stream.	Locality at which water was tested.	Temperature of water (°C.)	PH of water.	Remarks.
Aug. 15...	Rewa River.....	Viria village on eastern branch of Rewa River, above its junction with Waidina River.	24.8	7.25	When boiled and cooled to 28° C. it had 7.65 PH.
Aug. 15...	.....Do.....	Main stream, 7 miles below Viria; below junction with western branch.	.....	7.12	When boiled and then cooled to normal temperature (28° C.) it gave 7.6 PH.
Aug. 26...	Lamia River flowing into Suva Harbor.	Above lowest rapid, about 1 mile inland.	25	6.6	Boiling and then cooling to 27° C. gave a PH of 7.2.
Aug. 27...	Viseri River, the largest stream flowing into Suva Harbor.	.....Do.....	25	6.6	Boiling and then cooling gave 7.3 PH.
Aug. 29... 1920.	Naikoroko River, west of Suva Harbor.	Above lowest rapid.....	21.9	6.7	Boiling and then cooling to 28° C. gave 7.5 PH. 89 c. c. of this water at 6.7 PH and 11 c. c. of sea-water of 8.25 PH gave a mixture of 7.1 PH.
April 18..	.....Do.....	.....Do.....	25	[1]6.4	
Sept. 3....	Nauva River.....	About 5 miles inland, below the waterfalls.	23	7.35	Boiling and then cooling to 25° C. gave 7.6 PH. This water contained only 3 mg. of chlorine per liter of river-water.

[1]By methyl-red test.

Thus, Sir John Murray's idea that the stream-waters of volcanic islands might be sufficiently acid to be efficient solvents of reef limestones appears not to be supported, and as tests of the sea-water of the lagoon of Tortugas, Florida, made by Dole, Tashiro, McClendon, and others, show that there is practically no free

carbonic acid in this water, the Murray-Agassiz theory of the submarine solution of coral-reefs due to carbonic acid in the water appears to be refuted. As appears from table 20, direct rainfall into the sea is usually also a negligible factor in materially reducing the alkalinity of the waters of shallow reef-flats, for the buffer value of the carbonates of sea-water is so great that even torrential showers do not usually produce acidity. Thus, at the landing-stage of Blacklock's Wharf, near the shallow inner end of Pago Pago Harbor, the 7.8 inches of rain of March 19, 1917, reduced the alkalinity only from 8.2 to 8.185, and the torrential shower of 4.3 inches on April 12 reduced it to 8.0 PH, still leaving it decidedly alkaline.

Under normal conditions of wind, waves, and currents, rain-water falling into the sea is quicky mixed with so large a bulk of sea-water that its effect in producing dilution is but slight. When heavy rain falls during a flat calm, however, the rain-water tends to float over the surface of the sea-water and does not readily mix with it. Thus, at Blacklock's Wharf, near the inner end of Pago Pago Harbor, there was a very heavy shower which fell during a complete calm in the morning of July 2, 1920, and immediately after this shower had ceased the surface water showed chlorine 9.94 and salinity 17.97, while at a depth of 34 inches the chlorine was 14.7 and salinity 26.56. Also, at Judge Gurr's Dock at Maleota Harbor, on July 9, 1920, the surface water gave by titration chlorine 17.25 and salinity 31.17, while at a depth of 44 inches the water was chlorine 18.82 and salinity 34. The relatively brackish water was clean, and, floating over the deep-lying sea-water, it produced a refractive "wiggling" effect. Thus, under the rare condition of flat calm and heavy rain, the water over shallow reef-flats may become so diluted and muddy as to destroy many of the more delicate corals. In fact, vast numbers of *Acropora hyacinthus* were killed, even in water 10 feet deep, all along the shores of Tutuila by the torrential rains of 37.5 inches which fell between June 28 and 30, 1920; and even *Porites* heads fully 50 years old were killed at Fagaalu by the same shower.

To show that rain-water is a negligible factor in reducing the alkalinity of sea-water at Tortugas, Florida, in June 1919, it took 97 c. c. of sea-water of 8.23 PH mixed with 3 c. c. of rain-water of 4.75 PH to produce a mixture of 7.05 PH at 26.8° C This rain-water was collected in a "non sol" glass bottle, using a Pyrex glass funnel, and its PH was tested with methyl red. Its acidity was due to H_2CO_3; for upon being boiled in a test-tube of resistance glass its PH changed to 7.55 when cooled to 25° C. Further tests showed that 80 c. c. of rain-water of 4.75 PH and 20 c. c. of sea-water gave 7.4 PH. It is evident that in order to begin to dissolve reefs by virtue of its acidity, rain-water must almost wholly replace the sea-water, and this would quickly kill all reef-corals; so no reefs could grow in such a region.

The fact must be borne in mind, however, that tropical sea-water can not dissolve limestone, because it is already supersaturated with calcium, and is even precipitating calcium in places in the Florida-Bahama region. It seemed possible, however, that when diluted with stream-water it might be able to dissolve reefs, even though the mixture remained alkaline, but we find that calcium dissolves so slowly in diluted sea-water that no significant loss to the reefs can occur in this manner.

To test this, sea-water of 8.23 PH at 21° C. and 36.6 salinity was taken on January 15, 1919, from the lagoon of Tortugas, Florida, and analysis by Professor Alexander H. Phillips showed that it contained 0.4451 gram of calcium per 100 c. c. of sea-water. 2,500 c. c. of this sea-water was then mixed with an equal volume of distilled water of 5 PH, which contained no calcium by $AgNO_3$ test. This reduced the PH of the mixture to 7.15 at 24° C., and Professor Phillips found the calcium to be reduced to 0.2230 gram per 1,000 c. c. of water. 2,000 c. c. of this diluted sea-water was then placed in a glass-stoppered bottle of "non sol" glass, and 20 grams of limestone sand from the surface of the reef-flat of Aua, Pago Pago Harbor, Samoa, were placed in this water and the bottle was shaken at frequent intervals for a period of 24 hours, at 23.5° C., evaporation being prevented by the glass stopper. This caused the alkalinity to increase from 7.15 to 7.35 PH at the end of the experiment. Professor Phillips again determined the calcium and found it to be 0.2272 gram per 1,000 c. c. of water. Thus only 0.0042 gram of calcium per liter was dissolved, and so slight a solubility can not appreciably deepen the water over the reef-flats, for it is probable that the water over them is rarely reduced to 50 per cent of its normal salinity, for such a dilution would be fatal to all the reef corals, except *Porites*, in 24 hours.

To still further test the matter, 20 grams of the limestone sand from the Aua reef-flat were placed in 2,000 c. c. of the distilled water of 5 PH and shaken at intervals for 24 hours. This dissolved 0.0092 gram of calcium per 1,000 c. c. of water, or practically twice as much calcium as when the distilled water was mixed with an equal portion of sea-water. Thus the solution of limestone in the diluted sea-water was due almost wholly to the distilled water and not to the sea-water in the mixture, and apparently the ability of this diluted Atlantic sea-water to dissolve limestone is in direct proportion to the dilution, and is only slightly accelerated by so weak an acidity as PH 5.

The limestone sand used in this experiment had been drifted off the reef-flat of Aua by the currents and caught in the open mouth of a submerged barrel which was placed about 100 feet out from the shore, on the northern edge of the reef-flat. This sand was then washed repeatedly for a week in distilled water, until the washing water showed no trace of chlorine by $AgNO_3$ test. The sand was then dried over a water-bath at 100° C., and thrown into the diluted sea-water. This limestone sand was composed of fragments of nullipore algæ, corallines, corals, foraminifera, spicules of holothurians and alcyonaria, shells of mollusks, and fragments of volcanic rock, the last constituting by weight only 0.57 gram in 100 grams of sand.

The objection may reasonably be raised that acid distilled water is not thrown into the sea by the springs and streams of Pacific islands, and moreover, Pacific sea-water, due to its well-known paucity of pelagic plant-life, may be fully saturated with calcium and may behave differently from water of the tropical Atlantic.

To meet these objections, water from the large spring which provides drinking-water for the village of Pago Pago, Samoa, was mixed with water taken from the

surface of the sea 5 miles south of Breaker Point, Tutuila, and Professor Phillips determined the amounts of calcium, with results as follows:

1,000 c. c. of Pago Pago spring-water of 6.3 PH contains 0.0048 gram of calcium (Ca).
1,000 c. c. of Samoan sea-water of 35.37 per cent salinity and 8.25 PH contains 0.4366 gram of calcium.
1,000 c. c. of a mixture of equal parts of these waters, well shaken for 36 hours in a "non sol" bottle in the presence of 14 grams of limestone sand from the Aua reef-flat, dissolves 0.002 gram of calcium at 21 to 23.4° C.
1,000 c. c. of Samoan sea-water similarly shaken for 36 hours in the presence of 14 grams of Aua reef-flat sand dissolved no calcium in 36 hours.
1,000 c. c. of the Pago Pago spring-water similarly treated dissolved 0.0130 gram of calcium.

We see that the mixture of equal parts of sea-water and Samoan spring-water dissolved only 0.002 gram of calcium instead of 0.0065 gram, as might have been expected were the sea-water simply saturated with calcium, thus leaving unimpaired the solvent action of the spring-water in the mixture. Apparently, then, the Samoan sea-water is supersaturated with calcium, and when mixed with spring-water it reduces the solvent ability of the spring-water with which it mixes. It appears, then, that Samoan sea-water is practically incapable of dissolving limestone and that it retards the solvent action of Samoan spring-water mixed with it.

Professor Phillips made an analysis of the sea-water taken from the surface in a place where the depth was 8.5 fathoms, 5 miles south of Breaker Point, Tutuila, on September 19, 1919. The temperature of this water when collected was 29.1° C., its PH 8.25, salinity 35.3 per cent, and specific gravity 1.021.

The results are shown in table 21 in comparison with an analysis of sea-water from Tortugas, Florida, made by Dr. George Steiger, of the U. S. Geological Survey, in 1910.

TABLE 21.

Samoan sea-water analyzed by A. H. Phillips (grams per 1,000 c. c. of water).		Sea-water from Tortugas, Florida, analyzed by George Steiger (grams per 1,000 c. c. of water).	
Calcium (Ca)	0.4366	Calcium (Ca)	0.4420
Magnesium (Mg)	1.3512	Magnesium (Mg)	1.3054
Potassium (K)	0.3715	Potassium (K)	0.4000
Sodium (Na)	11.0793	Sodium (Na)	11.1957
Chlorine and bromine (Cl and Br)	20.1704	Chlorine (Cl)	20.0762
		Bromine (Br)	0.0644
Sulphur radicle (So_4)	2.7138	Sulphur radicle (So_4)	2.7422
Total	36.1228	Total	36.3516

McClendon (1918, Carnegie Inst. Wash. Pub. No. 252, pp. 252–258) shows that the surface water around the Florida Keys is supersaturated with calcium, and that it contains less than one-tenth as much fixed nitrogen as does the North Sea according to Raben, and thus bacteria and plant life in general have apparently almost removed the nitrates and nitrites from the sea-water. Evidently such water could not be expected to dissolve limestone, for calcium carbonate is being constantly precipitated in the Bahama-Florida region.

Crozier (1919, American Naturalist, vol. 54, p. 90) finds that the PH of the water of the lagoons of Bermuda ranges from 7.95 to 8.15, while that of the ocean

outside the reefs is 8.25 PH. Crozier surmises that limestone may be dissolved in these lagoons, but he did not analyze this lagoon-water and made no experiments to determine its efficacy in this respect. The reduction in alkalinity in these lagoons may be due to decomposing animal matter; but, even so, the lagoons remain alkaline and can not dissolve limestone unless their concentration of calcium is below saturation. Upon this we have no evidence, except the fact that similar lagoons in the Florida region are usually supersaturated with calcium.

Rainfall has remarkably little effect in diluting the water over reef-flats if these be in situations exposed to the waves and therefore favorable for the growth of corals. Thus, although on the average somewhat more than an inch of rain per day had fallen between January 1 and April 15, 1917, yet the salinity of the water at low tide over the shallow reef-flats off the southern end of the village of Aua, near the mouth of Pago Pago Harbor, was at the greatest reduced only to 31.00 per cent 50 feet or more from shore, the normal sea-water having a salinity of 34.83, and the average salinity for the reef-flat as a whole was 33.6 per cent at 29° C., and 8.23 PH.

When one considers that the average depth over the submerged parts of this reef-flat is only about 6 inches at lowest tide, the slight effect of heavy rains in diluting even wide areas of very shallow water becomes apparent.

One reason for this apparent anomaly is that rain-water, being of lesser specific gravity, does not readily mix with the underlying sea-water unless strongly agitated by waves and winds. Thus H. B. Bigelow (1917, Bulletin of Museum of Comparative Zoology at Harvard College, vol. 41, pp. 184, 196) shows that the surface waters of the Bay of Maine are generally 31.5 to 32.5 per cent salinity, but at a depth of 100 meters the water is 33 to 34 per cent.

Even great rivers seem to have but little effect in diluting the sea-water beyond the direct path of their outflowing current. Thus, on March 20, 1918, the muddy water of Mayaro Bay, Trinidad, within 50 miles of the mouth of the Orinoco River, had a salinity of 31.85, that of the tropical Atlantic being about 36.5.

It is a matter of common observation that there is a break in the coral-reefs opposite the mouth of every large stream, and experiments made at Tutuila enable us to assert that these cuts through the reef are, as Darwin surmised, places wherein the corals have been prevented from growing by the silt and dilution due to the stream in time of flood, and have not been dissolved out by the water of the stream. This was tested by placing reef-corals in a floating live-car 150 feet off the mouth of the large brook at Pago Pago Village, at the extreme inner end of Pago Pago Harbor, in a region where no corals appear to have grown. The bottom here is thickly covered with a soft, dark-brown volcanic mud brought down by the stream, and the water was usually brackish, the observed range in salinity being from 34.38 to 25.48 per cent, between March 27 and April 11, 1917. On April 12, however, 4.3 inches of rain fell during the morning and the stream was so greatly swollen that the salinity of the water at the live-car sank to 0.93, and even after 24 hours it had risen only to 9.24, that of normal sea-water being 34.83. (See table 23.)

Of the commoner reef-corals, 27 specimens were placed in the live-car in this situation, as follows: 4 branched *Acropora* related to *A. gracilis*, 2 *Acropora* aff. *pharaonis* from the seaward part of the reef-flat, 3 specimens of the stout-stemmed incrusting *Acropora leptocyathus*, which grows well only in the active wash of the breakers, 2 of the delicately branched *Acropora hyacinthus*, which finds its optimum conditions on the steep seaward slope of the reef-wall below the agitation of the waves, 2 *Fungia* sp., 3 massive *Porites lutea*, 4 of the branched *Porites andrewsi*, 3 *Pocillopora damicornis* var. *cespitosa*, 1 *Leptastrea purpurea*, 2 specimens of *Psammocora* aff. *ramosa*, and 1 *Pavona danai*. A coating of fine brown mud formed over the bottom of the live-car, and the *Acropora* began to fade in color and their polyps seemed unable to expand after 4 days, but all of the corals survived for 15 days until the torrential rain of April 12, 1917. During the following 24 hours, however, the salinity ranged between 0.93 and 9.24 and a coating of mud 3 mm. thick formed over the bottom of the live-car. This killed all the corals excepting 2 of the 3 specimens of massive *Porites* (*Porites lutea*), which, although injured and macerated in places, still survived, about three-quarters of its polyps being able to expand when replaced in normal sea-water. This species lives closer to the shore than does any other reef-coral of Samoa, and it is the only one which thrives near the mouths of streams, as at Fagaalu.

TABLE 22.—*Tests of hydrogen-ion concentration of rain-water at Pago Pago, Tutuila, Samoa, March 1917.*

Date.	Air temperature (° C.).	Amount of rainfall (inches).	Hydrogen-ion concentration of rain-water.	Remarks.
1917				
Mar. 26...	.....	1.8	0.126×10^{-5}	Rain-gage on Blacklock's Wharf, 8 feet above sea-level.
23...	24.4	0.3	$.135 \times 10^{-5}$	Rain-gage on crest of Vatia Pass, about 1,200 feet above sea-level.
16...	27	0.1	$.15 \times 10^{-5}$	Rain-gage on Blacklock's Wharf, 8 feet above sea-level.
13...	24.7	0.2	$.182 \times 10^{-5}$	Do.
19...	.....	6.0	.194	Do.
25...	.....	3.0	$.288 \times 10^{-5}$	Do.
12...	25	0.2	$.30 \times 10^{-5}$	Do.
19...	23.05	1.8	$.40 \times 10^{-5}$	Do.
18...	25	1.8	$.438 \times 10^{-5}$	Do.
Do...	24.5	1.4	$.678 \times 10^{-5}$	Do.
1919		Heavy shower	1.0×10^{-5}	Do.
Aug. 10...	26			
22...	26	.....do.....	$.741 \times 10^{-5}$	Do.

It is evident that, as Darwin surmised, the exceptional conditions of dilution and silt due to floods can destroy all corals which may have obtained a temporary foothold off the mouths of streams. A break appears in the reef-wall at such places, due to the fact that corals could never grow there, and not to solution of the reef by the fresh water of the stream.

TABLE 23.—*Tests of stream-waters of Tutuila Island, Samoa, March and April 1917.*

Place of Observation.	Temperature of stream. °C	Chlorine (grams in 1,000 grams of water).	PH of stream-waters.	Hydrogen-ion concentration of stream-water.
Small stream west of German store, Pago Pago, Mar. 18; after 3.2 inches of rain; stream swollen, but not muddy	25.2	.....	7.3	0.5×10^{-7}
Same stream swollen and muddy after 7.8 inches of rain Mar. 19, 1917.	24.6	.....	7.3	0.5×10^{-7}
Large stream entering harbor at Pago Pago Village, Mar. 11 at highest bridge of Fagasa Pass about 500 feet above sea-level, after 40 hours without rain	.....	.....	7.15	0.707×10^{-7}
Mar. 11 at Pago Pago Village, about 20 feet above sea-level	28.6	.....	7.15	0.707×10^{-7}
Mar. 30 at same situation	.....	.....	7.27	0.537×10^{-7}
At Pago Pago Village after 2.1 inches of rain, Mar. 17; about 20 feet above sea-level; stream turbid and swollen	25.7	.....	7.15	0.707×10^{-7}
Mar. 19, after 7.8 inches of rain, at Pago Pago Village, about 20 feet above sea-level; stream turbid and swollen	23.4	.....	6.97	0.107×10^{-7}
Small stream 30 feet above sea-level near NW. end of Point Distress, Pago Pago Harbor, Mar. 20, after 3.4 inches of rain during the day	.....	.....	7.37	0.425×10^{-7}
Large stream in Fagaalu Valley which falls over the waterfall. Mar. 8, after 13 inches of rain. At foot of waterfall	28.5	.....	7.42	0.38×10^{-7}
Mar. 8 at village of Fagaalu, 300 feet inward from sea-shore	28.9	.....	7.25	0.562×10^{-7}
From pool above lower waterfall and below long upper fall, Mar. 9, after 0.4 inch of rain during day	23.8	.....	7.4	0.298×10^{-7}
Large subterranean stream at Leone, issuing to surface in a basin about 15 to 20 feet in diameter and at once forming one of largest streams of island; flows under a lava-flow	24.6	.....	7.3	0.5×10^{-7}
Large spring near Pago Pago Village, Sept. 10, 1919	25.6	.....	[1] 6.3	0.5×10^{-6}
Spring on west side of Pago Pago Harbor near naval station; after 2.0 inches of rain of Mar. 14, 1917; spring dries up soon after rain	29.4	.....	7.1	0.794×10^{-7}
"Drinking spring," mouth of Fagaalu, west side of Pago Pago Harbor, Mar. 19, after 7.8 inches of rain; is a permanent spring	24.1	.....	7.37	0.425×10^{-7}
Same spring, Mar. 20, after 3.4 inches of rain during day; spring was but slightly affected by rains, its discharge being only little augmented	.....	0.002	7.42	0.38×10^{-7}
Seepage from a lava-cliff at Blunt's Point, Pago Pago Harbor, Mar. 19, after 7.8 inches of rain; seepage disappears in dry weather	25.3	.....	7.42	0.38×10^{-7}
Small spring about 800 feet above sea-level on the Pago Pago Harbor side of Vatia Pass, Mar. 20	.....	.....	7.4	0.398×10^{-7}
Spring near crest on Vatia side of Vatia Pass, about 1,000 feet above sea-level, filling an artificial rocky basin in side of lava-cliff and used for drinking purposes by pedestrians traveling over pass; Apr. 3, 1917	.....	.....	6.6	0.2505×10^{-6}
Same spring on Vatia Pass:				
Aug. 6, 1919	.....	.....	[2] 5.75	0.175×10^{-5}
Aug. 18, 1919	.....	.....	[2] 6.3	0.5×10^{-6}
July 20, 1920	.....	.....	[2] 5.4	0.398×10^{-5}
Spring issuing from a lava-cliff near Laulii Village, S. side of Mount Pioa, 60 feet above sea-level	.....	.....	7.15	0.707×10^{-7}
Spring east of Faleasau Village, Tau Island, and also another spring west of Aluulu Village on Ofoo Island, Aug. 29 to 30, 1919	26.1	.....	7.45	0.352×10^{-7}
Water from swamp in crater of Aunuu Island, July 12, 1920; water was dark brown in color, contained H_2S, and had a salinity of 0.024 per cent by $AgNO_3$ test	26.5	.....	[2] 6	1×10^{-6}
Mar. 19, 1917, at Fagaalu Village, about 500 feet in from seashore, after 7.8 inches of rain; stream much swollen and turbid	23.4	0.015	6.97	0.107×10^{-6}
Apr. 14, 1917, above cow pastures about 0.12 mile inland above Fagaalu Village, a carboy of water collected for analysis; stream clear and normal, after 0.2 inch of rain of Apr. 13	24.2	.....	7.3	0.5×10^{-6}
Small trickling stream about 0.25 mile west of Fagasa Village, about 200 feet above sea-level; in forest, densely shaded, Mar. 11	.....	.....	6.6	0.2505×10^{-7}
Largest stream of Fagasa Village, about 20 feet above sea-level and 500 feet above shore, Mar. 11	.....	.....	7.6	0.2505×10^{-7}
Same stream, about 0.5 mile from shore and 500 feet above sea-level	.....	.....	7.35	0.446×10^{-7}
Eastern one of 3 streams of Vatia Village, swollen by 3 inches of rain of Mar. 25, 50 feet above sea-level	.....	.....	7.27	0.536×10^{-7}
Largest (middle) stream of Vatia Village, swollen by rain of previous night, Apr. 15	.....	.....	7.48	0.3305×10^{-7}
Small stream on Pago Pago side of Vatia Pass, Mar. 23, 1917	24.1	.....	7.27	0.537×10^{-7}
Stream at Massefau, about 0.25 mile inland, quick water, Mar. 28	26.95	0.15	7.29	0.513×10^{-7}

[1] By methyl-red test. Boiled and then cooled to 26°C. gave 8 PH.

[2] By methyl-red test.

GROWTH-RATE OF SAMOAN CORALS.

By Alfred Goldsborough Mayor.

By far the most accurate and extensive observations upon the growth-rate of corals are those of Vaughan, published in Year Book No. 14, Carnegie Institution of Washington (pp. 221–231). Vaughan studied the corals of Tortugas, Florida, and of Andros Island, Bahamas. He reared the planulæ of several species and weighed and measured other corals with their bases embedded in concrete attached to tiles, which were staked out with iron stakes upon the reef-flats, and he also observed the growth-rate of corals growing naturally upon the reefs. All of the forms studied by Vaughan were shallow-water species, such as constitute the reefs of the Florida-Bahama region. He found that, on the average, corals of the genus *Acropora*[1] made an annual growth of 54 mm. in diameter and 35 mm. in height; branched *Porites* 26 mm. in diameter and 19 mm. in height; while the massive *Porites astræoides* grows 13 mm. in diameter and 5 mm. in height per annum. In the Pacific, however, massive *Porites* heads constitute a more important element as reef-builders than in the Atlantic, and I find that these corals in Samoa and Fiji appear to make an annual average growth of 31 mm. in diameter and 17 mm. in height; thus, apparently growing more than twice as rapidly as the Atlantic species. In the Atlantic, *Orbicella annularis* is probably the dominant large, massive coral of the seaward slopes of the reefs, taking much the place that massive *Porites* does in the Pacific; but its growth-rate according to Vaughan is very slow, being on the average only about 7 mm. in diameter and 6 mm. in height. Thus a reef composed of the massive *Porites* of the Pacific might grow upward three times as fast as one composed of the Atlantic *Orbicella annularis*. Vaughan estimates that a reef composed of *Orbicella annularis* might attain a thickness of 150 feet in between 6,500 and 7,600 years, and according to my estimate such a reef composed of the massive *Porites* of Samoa might develop in 2,700 years; but neither of these corals grows at depths of 150 feet, so such a reef would have to start on talus, or on a structure built up by the very slow-building corals which grow at depths greater than 20 fathoms.

The older literature upon the rate of growth of corals is reviewed in Dana's *Corals and Coral Islands* (1872, pp. 123–127; 249–257), but it will be unnecessary to refer to it in detail, for the data it provides are not precise enough to warrant basing conclusion upon it respecting the growth-rate of corals; for in no single case is the actual growth-period of any of the measured specimens known. This objection also applies to the observations of A. Agassiz (1890, Bull. Museum Comparative Zoology at Harvard College, vol. 20, p. 61–53, 4 plates), upon three corals

[1] For the names of the Samoan corals I am indebted to Dr. T. Wayland Vaughan and Dr. J. Edward Hoffmeister. Vaughan has decided that the name *Acropora* should replace the term *Madrepora* of many authors. Hoffmeister's report on the corals collected and experimented upon by Mayor appears as Publication 343 of the Carnegie Institution of Washington.

that had grown upon a telegraph cable between Key West and Havana, which had remained under water 7 years and during the whole or a part of this time had been growing at depths of 6 to 7 fathoms, near Key West. Of two specimens of *Orbicella annularis* one had grown 2.5 and the other 2.25 inches above the cable; one specimen of *Mæandra areolata* had grown 1 inch, and a specimen of *Isophyllia dispsacea* 2.5 inches above the cable

In June 1890, Saville-Kent measured and photographed certain corals growing off Vivien Point, Thursday Island, Australia, and some of these were remeasured by me in November 1913. These measurements would indicate that a *Symphyllia* had grown at the average annual rate of 1.88 inches in diameter during 23 years, a massive *Porites* had grown 1.95 inches in diameter per annum; and a large *Goniastrea* had made no growth, but had survived in good condition during the 23 years. Thus this *Porites* at Thursday Island seems to have made an average annual gain in diameter of 49 mm., whereas my average for 17 heads of massive *Porites* in Samoa, some of which were observed for 3 successive years, is 31 mm. per annum. Possibly, however, the growth of *Porites* on the Great Barrier Reef is more rigorous than in Samoa. Heads 20 feet and more in diameter are not uncommon in Australia, whereas the largest head I could find in Samoa was 9.6 feet in diameter.

The most reliable study of growth-rate of Pacific corals which has hitherto been published is that of J. Stanley Gardiner, *Fauna and Geography of the Maldive and Laccadive Archipelagoes* (Cambridge University Press, vol. 1, pp. 327–333, 1903). Gardiner observed the size attained by young coral stocks which had grown in an artificial channel through the reef at Hululu, North Male Atoll, Maldives, which had been cleared of all coral 3 years previous to his study. He weighed, measured, ascertained the volume, specific gravity, and area in square centimeters covered by these corals, and presents his results in the form of a table and concludes that the average upward growth of these corals was 77 mm. in not more than 3 years, and that if broken down into a sheet they would form a layer of limestone 24.2 mm. thick. Thus these corals made an average upward growth of 25.6 mm. per annum. This is nearly in accord with the 24 mm. which is my calculated general average increase in height for the corals of Samoa. As Gardiner says, this growth might give rise to a reef about 14.5 fathoms in thickness in 1,000 years; while according to my estimate a reef 13.5 fathoms in thickness might be formed in this time. This slight difference has no meaning, due to the large factor of error in such estimates, but the apparent agreement in our results would indicate that the modern reefs now constituting the atolls and barriers of the Pacific could readily have grown upward to sea-level from the floors of submerged platforms since the close of the last glacial epoch.

The growth-rate of corals of Cocos-Keeling Atoll has been studied by F. Wood Jones and reported in his well-known book on *Coral and Atolls*, 1912, and also in a pamphlet upon the *Rate of Growth of the Reef-Building Corals*, published in London in 1908. Wood Jones finds that corals do not grow steadily, but by fits and starts, with no apparent reason for this activity or for its absence. This is amply confirmed by my studies in Samoa. For example, a massive *Porites* in Pago Pago Harbor

grew 37 mm. in diameter in 1917–18, and then made no growth the following year; but in 1919-20 it again started to enlarge and amost made up its loss by growing 54 mm. in diameter in this last year. Wood Jones fastened copper bands to the stems of branching corals, the band being placed at a distance of 10 centimeters from the distal extremity. He then observed the growth made in 100 days and states that the average growth was 27.4 mm. in the 100 days, but unfortunately he tells nothing of what species of branching corals he studied, except that they were chiefly "Madrepores" (*Acropora*). In stating the growth-rate of massive forms he falls into error, for he states that such corals add 1/37 of their original circumference to their growth in 100 days, which amounts to practically one-tenth the circumference (or the diameter) in a year. Thus, according to Wood Jones a massive *Porites* 100 mm. in diameter would become 110 mm. in diameter at the end of a year, gaining 10 mm.; while a head 500 mm. in diameter would gain 50 mm. in the same time; or, as Wood Jones puts it, "a paradox is arrived at, for the older a coral is the faster it grows." This would indeed be a paradox were it true, but it is obviously untrue. For example, 8 massive *Porites* heads studied by me in Samoa had an average initial diameter of 339 mm. and made an average gain in diameter of 37.5 mm. per year; whereas 9 larger *Porites* heads having an average original diameter of 1,620 mm. made an average gain in diameter of 28 mm. per annum. In fact, the observations of Vaughan, as well as those made by me, indicate that young corals grow more rapidly than old ones and that in most and perhaps all species, after a certain size has been attained, growth practically ceases. Moreover, I find from studies made on *Porites clavaria* at Tortugas, Florida, that if a large coral which has ceased to grow, or is growing only slowly, be broken apart and its branches planted in concrete, these isolated branches continue to grow at the slow rate of the old stock and do not gain in growth-rate by being separated. The same is true if we girdle branches of old coral stocks of *Porites* by encircling them with a lethal mixture of corrosive sublimate and iodine, for then the tips of such physiologically isolated branches do not regain the growth-rate of young stocks, but still retain the reduced rate characteristic of senile corals. In fact, this "experiment" is often made in nature, for it is a common thing to find the hard part of a stem of *Acropora* or *Porites* girdled by sea-weed, millepora, or lithothamnium, and yet such a branch does not gain in growth-rate through being isolated from the stock.

But to return to the observations of Wood Jones, he states that his results are practically in accord with those of H. B. Guppy (1889, Scottish Geographical Magazine, vol. 5, pp. 573–575), who concludes that in the Cocos-Keeling Atoll massive forms of *Porites* grow upward between 12.7 and 19 mm. per year, while the branching *Porites* (*palmata?*) grows about 30 mm., and *Acropora* and certain forms of *Montipora* at least 100 to 125 mm. per year; and we may say that these figures would also apply quite well to the growth-rate of corals in the shallows of the reef-flats of Samoa.

Sluiter (1889, *Naturkundig Tijdschrift Nederland Indie*, Bd. 29, p. 375) found that a young reef, which grew up after the explosion at the Black Cliff of Krakatoa, had grown to a thickness of 200 mm. in not more than 5 years; but by contrast

with this rapid growth J. Stanley Gardiner (1901, Proc. Cambridge Philosoph. Soc., vol. 11, part 3, pp. 214–219) calculates that corals in Fiji give an upward growth of only 5.19 mm. per annum, or a thickness of 17 feet in 1,000 years. In 1903, however, in speaking of the corals of the Maldive Islands, he says a reef might grow upward at least a fathom in 60 years.

It may be significant that even the lowest estimates of the rate of reef-growth would allow ample time for the rims of modern atolls to have grown upward to the surface since the close of the last glacial epoch, even if this growth necessitated the formation of a reef-wall 60 fathoms high, which may have formed while the melting of the ice gradually raised the level of the ocean to approximately that of modern times, although the actual change in sea-level since glacial times has probably not been more than 30 fathoms.

EXPERIMENTS AND OBSERVATIONS.

Seven sets of experiments were carried out upon the growth-rate of corals between 1917 and 1920.

One set of observations (table 2) was made upon photographed, weighed, and measured corals which were collected from the Aua reef-flat on the eastern side of Pago Pago Harbor. Figures 1 to 49, plates 2–14, illustrate these corals. After being marked by attaching numbered brass tags to these corals by means of copper wire, some of them were fastened to iron stakes driven into the reef-flat in quiet water 400 feet from shore, in a region wherein *Porites* flourishes. Other colonies had their basal stocks embedded in concrete 700 feet from shore in a region wherein *Acropora* is dominant and the water is agitated by the surge from the breakers. In this way 50 corals were treated and 38 of these survived and were found in July 1918. Observations upon corals growing naturally and undisturbed upon the reef-flats of Pago Pago showed that these weighed, photographed, and planted corals appeared to grow at a normal rate, due probably to the fact that the planted corals were removed from the water only long enough to photograph and weigh them, and were at once replaced upon the reef-flat.

Another set of observations, referred to in table 3 and figures 50 to 52, plate 15, were made upon 22 coral-heads growing naturally upon the reef-flats of Pago Pago Harbor. These were first measured in April 1917 and again in July 1918.

A third series consisted of 20 corals which were collected by means of a diving-hood at depths of 2 to 3 fathoms off the seaward edge of the Aua Reef in a region moderately agitated by breakers. A dense clustering of *Acropora* occurs in this place, at least three-quarters of the surface of the submarine slope being covered thickly with these corals. The corals were removed from the water only long enough to number, weigh, photograph, and embed their basal parts in concrete on tiles which were then replaced at a depth of 2.5 fathoms, close to the place where they were collected. These corals were numbered 32 D to 51 D, and the results of this experiment are recorded in table 4 and in figures 32 D to 51 D, plates 19–26.

Another set of observations was made upon 7 specimens of *Acropora* (*Tylopora*) *leptocyathus* Brook which were growing naturally on the breaker-washed edge of a

reef-patch off Aua Village, Pago Pago Harbor. An idea of the appearance and association of these corals may be gained from plate IV, fig. B, and the results of the measurements and weighings are shown in table 5.

Two other series of observations were made upon massive *Porites* heads allied to *P. lutea* M. Ed. and H. and are recorded in tables 6 and 7 and illustrated by figure A of plate I which shows the appearance of 7 of the smaller heads which had been growing off Fagaalu Village, Pago Pago Harbor. The 9 larger heads which were growing naturally off Fagaalu and Utelei, Samoa, and Muaivuso, Fiji, are referred to in table 7.

In order to test the relative growth-rates of corals in the highly agitated shallow water of the upper surface of the reef-flat, and in deep, quiet water off the seaward edge of the reef, 24 corals of medium size from the upper surface of the Aua reef-flat were sawed into approximately equal halves. One-half marked S was embedded in concrete on the upper surface of a reef-patch off Aua, Pago Pago Harbor, in pure, highly agitated shallow water about 8 inches deep at lowest tides. The other half, marked D, was embedded in concrete on a tile and sunken to moderate depths off the edge of the same reef-patch on which the S series of corals was planted. Nos. 10 D to 12 D were grown from July 25, 1919, to June 12, 1920, in water 7 fathoms deep; Nos. 13 D to 24 D at a depth of 8.5 fathoms, and Nos. 25 D to 30 D at a depth of 5 fathoms. These sunken corals were in quiet water away from the surge of breakers and in a region in which we could detect no current by means of an Ekman meter. The bottom was covered with fine silt which clung like dust to every object and was at once fatal to all the *Acropora*. As none of these corals was in its natural environment, the water being either too agitated or too quiet, their growth-rates are not considered, but they are regarded merely as examples of the effects of agitation, or of stagnant water and silt, upon the growth-form of corals. The results are recorded in table 8 and are illustrated for the corals in pure, agitated, shallow water by figures 1 S to 24 S, and for the halves grown in deep, quiet, silted water by figures 1 D to 24 D, except that illustrations of the *Acropora* and others which died without growing are not shown. In general, the corals in agitated water produced short, thick-set stems, while those in the deep, quiet water developed long, slender stems. F. Wood Jones, in his *Coral and Atolls*, 1912, has well described these effects for *Pocillopora* and branched *Porites*, but our results show that *Psammocora*, *Pavona*, and even *Acropora* may also respond in a similar manner to these influences. Vaughan observed a similar response in an *Agaricea* grown in agitated water at Tortugas, Florida.

In order to determine the growth-rate of corals as affecting the development of the reefs, we must consider corals which die or do not grow as well as those which flourish, and take the average of the entire set of observations.

Some corals, such as the massive *Porites* and other huge heads, certainly live a century or more, but most of the species, such as the numerous *Acropora*, *Pocillopora*, and branched *Porites*, are short-lived and probably attain full growth in less than 10 years. Indeed, Vaughan showed that in *Favia fragum* of the Atlantic the growth is rapid during the first year, after which it declines, and in *Mæandra areolata*

there is a decided falling off in growth-rate after the coral has attained a length of about 60 mm. Not one of the *Acroporas*, *Pocilloporas*, and branched *Porites* measured by Saville Kent in 1890 off Vivien Point, Thursday Island, Australia, could be found by me in 1913, and in Samoa it was evident that *Acroporas*, which had attained to large size and perfection of condition, generally the next year showed signs of deterioration and were more or less covered with sea-weed, millepores, bryozoa, or lithothamnium, and had made little growth. Thus, if we confine our measurements to small heads, we will probably get a rapid growth-rate, whereas large senile heads will give much less. The endeavor was therefore made to select specimens of average size over the Samoan reefs.

If a coral gains 9 mm. in diameter in 9 months it may be expected to attain 12 mm. in 12 months, the dimensions following a linear ratio proportionate to the time; but if we wished to calculate the *weight* at the end of the year the problem would be more complex. In hemispherical or oval massive heads, such as *Porites lutea*, *Symphyllia*, or *Goniastrea*, the weight may be expected to increase as the cube of the diameter. Thus if D be the diameter at the beginning of the year and if d be the increase in diameter due to a year's growth, then if D^3 represent the weight at the beginning of the year, $(D + d)^3$ will represent the weight at the end of the year. Often, however, these corals grow in very shallow water and are thus killed on top at low tide-level, so that they can grow only laterally as a ring of living polypites constituting the vertical outer margin of a cylinder, and in this case the weight gained per annum must be simply proportional to the relative diameters of the cylinder at the beginning and at the end of the year.

In most of the branching forms, such as *Porites andrewsi*, and the numerous species of *Acropora* and *Pocillopora*, the branches radiate outward from a basal center, and as the coral grows new branches develop from the sides of the old ones, so that the tips of the branches always remain approximately at a constant distance apart. In these cases one would expect the weight to increase as the square of the average linear dimension. Thus, if a coral of weight (w) has an average dimension of (d), where $d = \frac{(\text{length} + \text{breadth} + \text{height})}{3}$, and if this coral grows so that it attains a weight w and an average dimension of D, then

$$W = \frac{D^2 w}{d^2}$$

This formula would be strictly true if the branches all arose from the base and not at various levels from the sides of older branches, and if they were cylindrical and not tapering conically from base to tip. It seems, however, that these two factors about offset each other; for taking the average gain in weight in 15 months made by 6 branched *Acropora*, 4 *Porites*, 4 *Pocillopora*, and 1 *Pavona foliosa* of Samoa it was found that the observed average weight at the end of the 15 months was 1.09 times the expected average weight as calculated by the formula given above, the calculated and the observed gain in weight thus being practically identical. Thus, if we observe the gain in weight made in somewhat more or less

TABLE 1.—*Temperature, chlorine, salinity, and hydrogen-ion concentration of harbor-water and sea-water of Tutuila, Samoa.*

Date.	Place of observation.	Water temp.	Chlorine by $AgNO_3$ test.	Salinity.	PH of sea-water.	Hydrogen-ion concentration.	Rainfall in 24 hours before observation.	Remarks.
1917		°C					*inches.*	
Mar. 12	Off mooring buoy No. B, Pago Pago Harbor.	29	.....	.....	8.185	0.652×10^{-8}	0.0	High tide.
18	....Do.....	28.4	16.59	29.97	8.21	0.615×10^{-8}	3.2	Do.
15	Off Blacklock's Wharf, midway across harbor.	29	.....	.....	8.23	0.588×10^{-8}	0.1	Tide one-third high.
18	....Do.....	28.4	17.6	31.80	8.2	0.63×10^{-8}	3.2	Rising.
12	Off Goat Island, Pago Pago Harbor, midway across harbor.	29	.....	.....	8.18	0.656×10^{-8}	0.0	High tide.
15	....Do.....	29	19.04	34.4	8.23	0.588×10^{-8}	0.1	Tide rising, one-third high.
12	Mouth of Pago Pago Harbor, between Breaker Point and Double Point.	29	19.28	34.83	8.23	0.588×10^{-8}	0.0	High tide.
27	2.5 miles south of Breaker Point, off Pago Pago Harbor.	28.5	19.29	34.85	8.23	0.588×10^{-8}	1.2	Do.
29	In open ocean 0.25 mile south of Point Steps, the southernmost point of Tutuila.	28.3	19.23	34.83	8.23	0.588×10^{-8}	0.0	Nearly high tide.
28	In open ocean 0.25 mile east of Cape Matutula, the easternmost point of Tutuila, 10^h30^m a. m.	28.2	19.28	34.83	8.25	0.563×10^{-8}	0.0	Tide rising, nearly high.
Apr. 14	....Do., 3^h40^m p. m.....	28.9	19.28	34.82	8.24	0.575×10^{-8}	2.0	Do.
July 12	....Do., 10 a. m.....	.....	19.3	34.87	.....	.....	0.0	
1920								
Mar. 28	Mangrove swamp at Massefau, upper part.	28.95	3.36	6.09	7.63	0.234×10^{-7}	0.1	Dark-colored swamps shut off from the sea by recent sand dunes.
28	Massefau, lower part of swamp near sea.	27.5	3.11	5.64	7.4	0.398×10^{-7}	0.1	
29	Mangrove swamp at Leone, Tutuila.	28.4	1.9	3.46	7.5	0.317×10^{-7}	0.0	
12	Off Pago Pago Village at inner end of Pago Pago Harbor.	29	18.025	32.56	8.18	0.660×10^{-8}	0.0	About 150 feet off mouth of large stream which enters harbor at Pago Pago Village. The live-car containing corals was placed here.
15	....Do.....	29	18.99	34.31	8.23	0.588×10^{-8}	0.1	
20	....Do.....	27.5	15.65	28.28	8.17	0.676×10^{-8}	3.4	
25	....Do.....	27.9	16.66	30.10	8.2	0.630×10^{-8}	3.0	
31	....Do.....	.....	15.05	27.2	8.185	0.652×10^{-8}	1.0	
Apr. 2	....Do.....	.....	14.01	25.32	8.18	0.656×10^{-8}	0.3	
4	....Do.....	30.9	17.37	31.38	8.18	0.656×10^{-8}	0.2	
6	....Do.....	29.2	15.1	27.29	8.1	0.795×10^{-8}	0.2	
12	....Do.....	24.8	0.502	0.93	7.33	0.831×10^{-7}	4.3	
13	....Do.....	25.4	5.1	9.24	7.8	0.25×10^{-7}	0.2	
Mar. 6	Landing-stage of Blacklock's Wharf, inner part of Pago Pago Harbor.	29.8	.....	.....	7.75	0.3×10^{-7}	0.7	Low tide.
6	....Do.....	28.2	.....	.....	8.05	0.890×10^{-7}	0.7	High tide.
8	....Do.....	29	17.73	32.03	8.2	0.630×10^{-8}	1.3	Low tide.
11	....Do.....	29.4	19.38	35.01	8.2	0.630×10^{-8}	0.0	Tide one-half high, rising.
13	....Do.....	28.5	11.78	21.29	8.07	0.850×10^{-8}	0.2	Low tide.
16	....Do.....	27.2	18.51	33.44	8.17	0.675×10^{-8}	0.1	Do.
16	....Do.....	.....	18.84	34.04	8.23	0.588×10^{-8}	0.1	High tide.
17	....Do.....	27.2	18.51	33.44	8.17	0.676×10^{-8}	2.1	Low tide.
17	....Do.....	27.6	18.535	33.48	8.14	0.725×10^{-8}	2.1	Rising, nearly high tide.
18	....Do.....	25.4	13.42	24.25	8.1	0.795×10^{-8}	3.2	Nearly low tide, still ebbing.
19	....Do.....	26.9	16.86	30.46	8.185	0.652×10^{-8}	7.8	Ebbing tide, nearly low.
Apr. 12	....Do.....	26.6	8.58	15.52	8.0	$1. \times 10^{-8}$	4.3	Low tide.

than a year we can calculate the gain in a year with at least some degree of confidence.

In order to determine the growth-rate of the reef as a whole we must be careful to consider the relative abundance of the various kinds of corals. Thus in the most rapidly growing genus, *Acropora*, we find that in the shallows along the breaker-washed seaward edge of the reef *Acropora* (*Tylopora*) *leptocyathus* is the dominant coral, for its short, stout, conical stems, arising from a thick, expanded base clinging securely to the reef-floor, can resist the pounding of the surf as can no other species. This coral grows more slowly than any other *Acropora*, making an average gain of about 30 mm. in diameter per annum and very much less in height, attaining practically no upward growth after it has gained a height of 50 to 60 mm. This species is also an important element of the reef in deep, pure water off the seaward edge, where the surge of the sea produces considerable stirring of the water. (See fig. A of plate III.)

Another important element in reef formation in Samoa is *Acropora hyacinthus* (Dana), which is abundant over the shallows of the reef-flats in places somewhat protected from the breakers, but where there is considerable current and the water is free from silt. It is also a very important element of the seaward slope of the reef, its vase-shaped stocks covering wide areas, often to the exclusion of other forms. This coral grows rapidly, gaining about 100 mm. in diameter and 44 mm. in height per annum.

The third important element among the Samoan *Acropora* is seen in the forms well represented by *Acropora* (*Tylopora*) *samoensis* Brook, whose relatively long, nearly cylindrical stems radiate outward from a somewhat massive base. These forms grow almost as rapidly as *A. hyacinthus*, gaining about 89 mm. in diameter and 63 mm. in height per annum.

The fourth important element among the many acroporas is the tree-like form with branched and tapering conical stems, well exemplified by forms related to *A. cribripora*, *A. pulchra*, and *A. haimii*. The growth-rate of these forms is most rapid of all among *Acropora*, appearing to be on the average about 220 mm. in diameter and 120 mm. in height per annum in Samoa; and this appears to accord with Guppy's and Wood Jones's determinations of the growth-rate of related forms in the Cocos-Keeling Islands.

In estimating the increase in limestone due to growth of *Acropora* on the reefs, I would be inclined to give about equal weight to each of the four types described above. Thus, if all corals lived and grew normally, the growth-rate of *Acropora* as a whole over Samoan reefs would be about 110 mm. in diameter and 57 mm. in height, but due to the considerable death-rate and the poor growth of some individuals, my experiments recorded in the subsequent tables indicate that the effective rate is nearer 76 mm. in diameter and 30 mm. in height. This, however, gives no idea of the rapidity with which *Acropora* could build up a reef, for after death their fragile stems, unless coated with living lithothamnium, soon break and are scattered broadcast over the floor of the reef. On the seaward slope of the reef, however, under the surge of the breakers in depths of 1 to 6 fathoms

Acropora constitutes the determining element in the growth of the reef. These corals in this pure, agitated water grow most vigorously and develop stout, short, stumpy stems capable of resisting the force of the surges, thus making, according to my observations, only an average of about 19 mm. upward growth per annum, for corals do not readily raise their heads in regions where the surges are persistently tending to break them off. The average lateral growth is, however, 74 mm. per annum. This upward growth of 19 mm. is practically a permanent accession to the reef, for when they die these corals are thickly veneered with layer upon layer of lithothamnium, binding their tangled stems into a stout meshwork, into the interstices of which sand and loose fragments lodge to solidify the whole into permanent reef-rock.

Using a diving-hood, I have gone down on the seaward edge of the Aua Reef, when the lessening of the breakers would permit such action, and made a study of the relative abundance of the various genera of corals. I had hoped to be able to stake out areas 25 feet on the side and to count all corals within them, as was done on the shallow upper surface of the reef-flat, but the extreme irregularity of the surface made this impossible, and the difficulty was still further accentuated by the surges, which tended to throw one off one's feet, or into intricate caverns from which it might be difficult to escape. In the pure ocean-water, at depths of 1 to 6 fathoms under the breakers, the corals grow with a vigor unseen elsewhere. The individual stocks are many times larger than those of the same species growing in the shallow water on top of the reef-flat. Stocks of *Acropora hyacinthus* 3 feet in diameter are common, as are also branching *Acropora* covering 25 square feet in area. About three-fourths of the area of the seaward slope down to 4 to 6 fathoms off the Aua Reef is completely covered with coral-heads. The stems and stocks of these corals are stouter and of stronger build than those of corresponding species growing in the relatively quiet water of the shallows on top of the reef-flat. In strongly agitated water, corals thicken their stems and grow laterally rather than upward. Making use of a white board and a pencil tied to a string it was possible to take elaborate notes upon the reef conditions while one walked around among the coral-heads at depths down to about 6 fathoms. It was thus possible to count the number of heads of each species over definitely defined areas, and in this manner we found that off the seaward edge of the Aua Reef the coral-heads at depths of 2 fathoms and below consisted of 87 per cent *Acropora*, 10 per cent *Pocillopora*, and 3 per cent of all other forms, such as *Porites*, *Millepora*, *Alcyonaria*, etc. Thus the corals of the seaward slopes of the reefs of Tutuila consist chiefly of *Acropora*, the fastest growing of all corals.

Moreover, the overhanging seaward edge of the flat upper part of the reef is composed chiefly of *Acropora leptocyathus*, which, after it dies, remains bound to the reef by a veneer of lithothamnium. Beneath this overhanging edge there is a precipice or steep slope of from about 1 to 6 fathoms, at the base of which *Acropora* clusters thickly. Thus the reef grows seaward by the formation of an overhanging edge at low-tide level, which often breaks off and, falling to the bottom of the slope, aids in the upbuilding of the reef. Also at the bottom of the initial precipice, and

down the seaward slope to depths of 6 to 7 fathoms, we find a dense growth of *Acropora* tending to build the reef upward and outward. Below 6 or 7 fathoms these corals become smaller and are farther apart, and the slope, which is about 30°, consists chiefly of dead coral which has rolled down from above, forming a talus.

There is doubtless a limit to the upward growth of the dense masses of *Acropora* which lie at the base of the reef precipice, for the breakers would destroy their stems should they approach too close to the surface. Thus the overhanging lithothamnium-veneered edge of the reef advances seaward at low-tide level, due chiefly to the growth of *Acropora leptocyathus*, which alone can withstand the full force of the breakers, and its fallen fragments serve to build up the wall to sea-level. Taking the average upward growth of the *Acropora* composing the seaward wall of the reefs of Tutuila to be 19 mm. per annum, and assuming that half of this (9 mm.) is effective, the reef might be expected to build itself upward 29.5 feet in 1,000 years, and this estimate is, I think, very conservative, for the remarkable growth of lithothamnium in the pure agitated water of the seaward slope of the reefs binds all dead coral into a firm network. I am inclined to believe, however, that due to this binding and veneering property of lithothamnium, which prevents the coral rock from decomposing after the death of the polypites, the entire 19 mm. per annum is effective in building up the reef, and thus an *Acropora* reef 10 fathoms thick might form in 1,000 years.

In silted regions *Porites* replaces *Acropora* to a considerable degree, so that in the Utelei side (western side) of Pago Pago Harbor branched *Porites*, massive *Porites*, and *Psammocora* are important elements in the formation of the seaward wall of the reef. Massive *Porites* in Samoa, according to my studies, makes an average upward growth of 17 mm. per annum, and this is a permanent accession to the reef. The branched *Porites* makes an upward growth of about 30 mm. per annum, but after death its stems break down unless veneered with lithothamnium, which does not grow readily in quiet water or in silted regions. It seems fairly safe, however, to say that a reef-wall composed of massive *Porites* might attain a thickness of 55 feet in 1,000 years, while a reef composed of branching *Porites* might grow upward at least 25 feet in the same period of time.

We are led to suspect that *Porites* is about as effective as *Acropora* as a reef-builder, from the fact that the reef on the eastern side of Pago Pago Harbor, which is predominantly *Acropora*, is no wider than that on the western side, which is largely *Porites*. Such estimates are of value only in that they indicate that the fringing reefs now surrounding Tutuila might readily have been formed since the close of the last glacial epoch. Our borings through the fringing reef in Pago Pago Harbor ran into hard basalt at a depth of 120 feet underlying the reef off Utelei, close to its seaward edge, 925 feet from shore. Another boring through the same reef 575 feet from shore ran into basalt at a depth of 121 feet, while 200 feet from shore the thickness of the reef down to its basaltic base was 68 feet. On the "Aua Line" of the Aua Reef, 512 feet from shore, hard basaltic rock was found at a depth of 156 feet. Thus at our most conservative estimate, the Utelei Reef might have been built up in 5,000 years. The following table gives the average

annual growth-rate of Samoan corals according to my observations, recorded in tables 2 to 8, inclusive. In this estimate corals which died or made poor growth are given equal weight with those which throve well.

Annual growth-rate of Samoan corals.

Genus of coral.	Average size in mm. at beginning of year.		Gain in diam. or lateral growth in mm. per annum.	Gain in height in mm. per annum.	Average gain in weight in grams per annum.
	Diam.	Height.			
Acropora	80	60	76	30	501
Pocillopora	70	53	36	23	272
Branched Porites	92	62	44	30	222
Massive Porites	1,027	.....	31	17	...
Pavona	117	68	39	32	34
Psammocora*	84	65	18	14	85
General average	.....	.....	41	24	...

*The colonies of *Psammocora* are so readily broken that this statement of growth is certainly less than that actually made.

In order to calculate the weight of dried stony matter, free from water or animal matter, which Samoan coral-heads of average size add to the reef-flats per annum, the weight of the living coral was ascertained both in 1917 and in 1918. Then in 1918 the coral was killed and its animal substance macerated or dissolved in KOH, after which the fresh water was largely abstracted by washing the skeleton in 90 per cent ethyl alcohol; the coral was then dried in the sun and weighed. This showed that the weight of the dried stony substance in various species of reef corals is on an average about 0.8 that of the same coral-head when alive. Various species of *Acropora* ranged from 0.07 to 0.9, while branched *Porites* were about 0.8, and large massive *Porites* slightly above 0.9.

Applying this correction, we find that on the Samoan Reef the gain in weight per annum of stony substance in various coral-heads of average size over the surface of the Aua reef-flat appears to be as follows: *Acropora*, 16 ounces; *Porites*, 7 ounces; *Pocillopora*, 9.5 ounces; *Pavona*, 12 ounces; *Psammocora*, 3 ounces avoirdupois. Knowing the number of coral-heads of these genera upon a reef-flat, we have a rough means of ascertaining the weight of limestone added to the reef each year by the growth of coral upon its upper surface.

By counting the numbers of coral-heads and species of corals on squares of 24 feet on the side (576 square feet), the squares being staked out from 50 to 100 feet apart from the shore to the seaward edge of the Aua reef-flat, we are led to the following conclusions:

On the upper surface of the Aua reef-flat between Breaker Point, Pago Pago Harbor, and the southern end of Aua Village, the area of the reef being 2,550,000 square feet, the numbers of corals are approximately as shown at top of page 65.

TABLE 2.—*Growth of corals on the reef-flat near the Aua Line, April 10, 1917, to July 10, 1918.*

No. of photograph and name of coral.	Description and remarks.	Dimensions, Apr. 10, 1917.	Weight of living coral Apr. 10, 1917.	Observed gain in dimensions in 15 months.	Observed gain in weight of living coral in 15 months.	Calculated gain in dimensions in 12 months.	Calculated gain in weight of dried stony substancein 12 months.	Calculated gain in weight of living coral in 12 months.
		millimeters.	*grams.*		*grams.*		*grams.*	*grams.*
1. *Acropora hyacinthus* (Dana).	Brown-purple with pink tips to branches. Branches delicate; found in water about 1 foot deep at low tide in region of breakers 790 feet from shore; planted at 700-foot station.	100.5 × 87 across top × 82 high.	.....	274.5 × 214 × 49 height.	.....	220 × 171 × 39 height.	.....	.....
2. *Porites andrewsi* Vaughan.	Brown-olive-colored branched *Porites* from about 600 feet from shore in water about 10 inches deep at low tide; grown at 400-foot station.	61.5 × 57 × 47.5 ...	28	53 × 52 × 60.5.....	269	42.5 × 42 × 48.5 .	167	215
3. *Porites andrewsi* Vaughan.	Brown-drab-colored branched coral from almost 600 feet from shore in water about 8 inches deep at low tide; grown at 400-foot station.	93 × 78 × 52.....	57	59 × 38 × 55	281	47 × 30.5 × 44...	156	232
4. *Porites andrewsi* Vaughan.	.....Do.....	125 × 98 × 80	198	51 × 36 × 25	268	41 × 29 × 20	179	215
5. *Pocillopora damicornis* var. *cespitosa* Dana.	Nos. 5, 6, and 7 were collected about 600 feet from shore in water about 8 inches deep at low tide and grown at 400-foot station.	55.5 × 54 × 40.5 ...	28.5	78.5 × 76 × 50.5 ...	347	63 × 61 × 40	211	264
6. *Pocillopora damicornis* var. *cespitosa* Dana.	.....Do.....	82 × 77 × 56.5.....	99	40 × 25 × 46.5.....	191	32 × 20 × 37	125	153
7. *Pocillopora damicornis* var. *cespitosa* Dana.	.....Do.....	84 × 71.5 × 62.....	269	108 × 95.5 × 76....	709	86.5 × 76.5 × 61 .	429	502
8. *Acropora hyacinthus* (Dana).	Nos. 8 and 9 grew side by side on one base of dead coral; they were purple-brown with pink tips to branches, found in rough water 700 feet from shore; planted at 700-foot station.	38 × 37 × 47	Nos. 8 and 9 combined 198.5.	91 × 36 × 53	Nos. 8 and 9 combined 737.	73 × 29 × 42	Nos. 8 and 9 combined 482.	595
9. *Acropora hyacinthus* (Dana).	.....Do.....	62.5 × 58.5 × 62 ...	.....	147.5 × 88.5 × 37 ..	.....	118 × 69 × 29.5..	.....	.....
11. *Acropora* aff. *A. humilis* (Dana).	Light-brown with violet tips; short blunt stems, found in breakers 790 feet from shore; grown in quiet water at 400-foot station; it barely survived; this coral does not live near shore, but thrives in rough water.	75 × 58.5 × 46.....	127.6	11 × 23.5 × 14.....	113	9 × 19 × 11	79	91
12. *Acropora* (*Tylopora*) *samoensis* (Brook).	Dark brown, thick stems; found 700 feet from shore in agitated water; grown at 700-foot station; damaged by forcible contact with a piece of dead *Acropora*, which it had practically overgrown.	82 × 83 × 84	141.7	90 × 22 × 71	.....	72 × 17.5 × 57...	.....	.....
13. *Acropora* (*Tylopora*) *leptocyathus* (Brook).	Light brown, thick, short stems; taken from region of breakers where it thrives and grown at 700-foot station in a region of relatively quiet water, where it died and became covered with lithothamnium and bryozoa.	77.5 × 73 × 20, made very little growth before it died.	.....	6.5 × 0 × 0.....	.....	.....	.....	.....
14. *Acropora hyacinthus* (Dana).	Dark purple brown with pink tips to the slender stems; taken from rough water 750 feet from shore; grown at 700-foot station.	44.5 × 34.5 × 53 ...	.....	134.5 × 138.5 × 114	.....	108 × 111 × 91 ..	.....	.....

16. *Acropora* (*Tylopora*) *samoensis* (Brook).	Light brown, with stout, moderately short branches taken from agitated water 8 inches deep at lowest tide and 750 feet from shore, grown at 700-foot station.	87 × 82 × 65, with 20 main branches in 1917 and about 100 in 1918.	142	116 × 94 × 55	510	93 × 75 × 44	364	384
17. *Porites andrewsi* Vaughan.	Green color, slender branches; from quiet water 8 inches deep and 400 feet from shore; grown at 400-foot station.	123 × 96 × 68	284	61 × 72 × 9	553	50 × 57.5 × 7....	337	450
18. *Acropora* (*Polystachis*) *cymbicyathus* (Brook).	From rough water about a foot deep at low tide and 750 feet from shore, grown at 700-foot station.	227 × 177 × 80, nearly full grown in 1917; it made little growth by 1918.	.....	12 × 21 × 5	.....	10 × 17 × 4	.....	.....
19. *Acropora teres* (Verrill).	Brown stems; common on reef-flats in region wherein surges die out in ordinary weather; taken from about 680 feet from shore in water about a foot deep at low tide; grown at 700-foot station.	85.5 × 60 × 68; in 1917 it had about 13 main and about 10 short side branches; in 1918 it had more than than 257 branches.	57	338.5 × 331 × 166..	1985	271 × 265 × 133 .	1,113	1383
20. *Favites abdita* (Ellis and Sol.)	Light olive-brown with vivid green centers to polypites; found about 650 feet from shore and grown at 700-foot station; specimen incrusting a dead acropora.	83 × 52.....	.....	24 × 35	.....	19 × 28.....	.....	.....
22. *Acropora* (*Tylopora*) *leptocyathus* (Brook).	Light brown, short, thick-stemmed, acropora from region of breakers, where it thrives; grown at 700-foot station, where it did not flourish.	117 × 116 × 48	241	43 × 26 × 5	354	34.4 × 21 × 4....	227	284
23. *Pavona decussata* Dana.	From about 500 feet from shore in quiet water about 8 inches deep at low tide in a region where this coral flourishes; grown at 400-foot station.	105 × 91 × 64	312	47 × 34 × 41	347	38 × 27 × 33	238	278
24. *Acropora vanderhorsti*, Hoffmeister.	Long-stemmed, stout-branched, brown-colored acropora from 650 feet from shore in water about 14 inches deep at lowest tide; grown at 700-foot station.	110 × 123 × 84; in 1917 it had 10 main branches, the longest 84 mm.; in 1918 it had 47 branches, the longest 160 mm.	85	136 × 141 × 106 ...	355	109 × 113 × 85 ..	215	268
28. *Pocillopora damicornis cespitosa* Danas (*brevicornis* facies.)	Massive short-stemmed pocillopora from rough water 750 feet from shore; grown in quiet water at 400-foot station, where it did not thrive.	108.5 × 68 × 52....	326	36.5 ×40 × 32.....	149	29 × 32 × 25	78	91
29. *Acropora corymbosa* (Lamarck).	Brown stems with pink tips; from water about 8 inches deep at low tide 600 feet from shore; grown at 400-foot station; this coral thrives in quiet water about 600 feet from shore.	66 × 63 × 55	284	53 × 59 × 37	397	42.5 × 47 × 30...	228	278
30. *Pocillopora eydouxi* M. E. and H.	Pink-colored, stout, short-stemmed coral growing in rough water; taken from region of breakers 780 feet from shore and grown at 700-foot station, where it thrives well.	104.5 × 60.5 × 57 ..	.....	23.5 × 24.5 × 59 ...	.....	19 × 20 × 47	.....	.....
32. *Acropora* (*Tylopora*) *leptocyathus* (Brook).	Light brown with short, stout stems from region of breakers where it thrives; grown 700 feet from shore in relatively quiet waters, where it soon died.	108 × 94.5 × 51....	.....	13 × 4.5 × 0.....	.....	10 × 4 × 0	.....	.....

TABLE 2.—*Growth of corals on the reef-flat near the Aua Line, April 10, 1917, to July 10, 1918.*—Continued.

No. of photograph and name of coral.	Description and remarks.	Dimensions, Apr. 10, 1917.	Weight of living coral Apr. 10, 1917.	Observed gain in dimensions in 15 months.	Observed gain in weight of living coral in 15 months.	Calculated gain in dimensions in 12 months.	Calculated gain in weight of dried stony substance in 12 months.	Calculated gain in weight of living coral in 12 months.
33. *Acropora* (*Conocyathus*) *valida* (Dana).	Brown stems with pink tips from region of breakers in water 1 foot deep at low tide; grown at 700-foot station.	154 × 130 × 79	.....	70 × 76 × 16	.....	56 × 61 × 13	.....	.....
34. *Acropora hyacinthus* (Dana).	Brown stems with pink tips; from water 10 inches deep at low tide, 750 feet from shore.	67 × 45 × 80	85	223 × 135 × 57	992	178 × 108 × 46...	564	723
35. *Acropora* (*Tylopora*) *leptocyathus* (Brook).	Light brown, short, thick stems, from breakers about 800 feet from shore; grown at 700-foot station, where it did not thrive.	107 × 90 × 29	.....	15 × 17 × 11	.....	12 × 14 × 9	.....	.....
36. *Leptastrea purpurea* (Dana).	From about 550 feet from shore in quiet water; grown at 700-foot station; it was three-fourths dead in 1918 and had made no growth.	38 × 27 × 24	128	0.....	.....	.....	.....	.....
37. *Porites* aff. *P. lutea* M. Edw. and H.	3 small colonies of massive points; probably detached from a larger head; grown at 400-foot station.	Largest 77 × 48 × 25; medium size 28 × 22; smallest 12 × 10.	.....	Largest 14 × 14 × 20; medium 6 × 1 smallest 8 × 7.	.....	Largest 11 × 11 × 16; medium 5 × 0.8; smallest 6.5 × 6.	.....	.....
38. *Acropora* aff. *formosa* var. *gracilis* (Dana).	Long branches, light brown with violet tips; from water about 2 feet deep, 600 feet from shore, grown at 400-foot station; only 1 of the 6 original branches lived, but this one made a good growth.	6 branches, longest 56 mm., shortest 26 mm. long.	42.5	8 main and about 132 terminal branches; branches had grown about 231 mm. in length; dimensions of stock in 1918, 298 × 241 wide × 287 high.	383	Growth of branches 185 mm. in length, in 12 months.	249	306
39. *Psammocora contigua* var. *maldivensis* Gardiner.	Dark olive-brown with very fragile stems, living only in quiet water; taken from about 400 feet from shore; grown at 400-foot station.	85 × 76.5 × 55.....	100	21 × 23.5 × 18.....	128	17 × 19 × 14	79	102
40. *Psammocora contigua* var. *maldivensis* Gardiner.	Do. Specimen badly broken in 1918.....	127.5 × 100 × 82.5 .	198	28.5 × 44 × 3.5 badly broken.	43	.....	.....	.....
41. *Psammocora contigua* var. *maldivensis* Gardiner.	Do. Very badly broken in 1918.....	81 × 62 × 52	71	3 × 19 × 0	.....	.....	.....	.....
48. *Galaxea fascicularis* (Linn.).	From a crevice in region of breakers 760 feet from shore, grown at 700-foot station.	109 × 71 × 40 nearly full grown.	397	7.5 × 5 × 5.....	29	6 × 4 × 4	17	23
49. *Pavona frondifera* Lamarck.	Fragile, foliated, light brown *Pavona* common 450 feet from shore, where it was found in water 10 inches deep at low tide; grown at 400-foot station.	135 × 126 × 71.5...	765	73 × 15 × 18.5.....	539	58.5 × 12 × 15...	317	431

About 502,200 heads of *Porites* grow over 72 per cent of the area of the upper surface of the reef-flat and contribute (due to their growth) 246,000 pounds of limestone per annum.

347,500 *Acropora* distributed over 56 per cent of the reef-flat contribute annuly 465,400 pounds of limestone.

57,600 heads of *Pocillopora* scattered over the entire reef-flat contribute 30,300 pounds of limestone.

55,900 *Psammocora* distributed over 30 per cent of the reef-flat contribute each year 11,000 pounds of limestone.

15,500 *Pavona* found over 35 per cent of the reef-flat contribute each year about 11,600 pounds of limestone.

Thus the growth of these corals appears to add about 764,300 pounds of limestone each year to the upper surface of the reef-flat, this limestone being estimated as dried and free from animal matter; and as these genera contribute 95 per cent of the entire coral-heads of the reef-flat, it is probable that about 800,000 pounds of limestone are added to the reef-flat each year by the growth of the corals over its surface, or about 2.8 pounds per square yard; or, taking the specific gravity of limestone as 1.8, this would be equivalent to a layer of coral about 8 mm. in thickness per annum over the entire reef flat; and as we have shown in the paper upon *Causes which tend to Maintain a Constant Depth over Pacific Fringing Reef-flats*, this is about the amount the reef is degraded each year.

The corals of Samoa are more effective as reef builders than are those of the Atlantic according to Vaughan. The massive *Porites* of Samoa which takes the place of *Orbicella annularis* of the Atlantic grows upward about 17 mm. per annum instead of 6 to 7 mm., as does the Atlantic *Orbicella*. Moreover, one never sees in the Atlantic anything like the dense clustering of vigorous stocks of *Acropora*, such as characterize the seaward slopes of the Samoan reefs. A far greater proportion of the ground is covered by corals in Samoa than on the Atlantic reefs, and while the growth-rate of Samoan *Acropora* is only slightly greater than that of the Atlantic species according to Vaughan, yet the far greater abundance of this genus over the Samoan reefs causes it to be more effective as a reef builder than are the Atlantic *Acropora*. In middle Oligocene times the Atlantic reefs were probably comparable with those of the modern Pacific, but the Atlantic reefs have been impoverished by the dying out of many forms which still survive in the Pacific.

Table 2 shows the growth of corals on the Aua reef-flat near the "Aua Line," east side of Pago Pago Harbor, Samoa, from April 10, 1917, to July 10, 1918. These corals were photographed, weighed, measured, and marked with serially numbered yellow metal tags attached to the corals by copper wire. The photographs bear numbers corresponding to those on the metal tags. Nos. 2 to 7, 11, 17, 23, 28, 29, 37 to 39, 40, 41, and 49 were attached by iron wires to iron stakes driven into the reef-flat 400 feet from shore, in quiet water 9 inches deep at low tide. The basal parts of Nos. 1, 8, 9, 12 to 14, 16, 18 to 20, 22, 24, 30, 32 to 36, and 48 were embedded in concrete near the outer edge of the Aua reef-flat 700 feet from shore in agitated water about 18 inches deep at low tide in a region wherein the breakers just die out in ordinary weather.

In 1918, the animal matter was removed by maceration and then the corals were soaked in KOH, which was removed by 90 per cent ethyl alcohol, after which the

TABLE 3.—*Gain per annum in linear dimensions of corals growing naturally in Pago Pago Harbor, Tutuila, Samoa, 1917 to 1918.*

Locality.	Description and name of coral.	Dimensions in millimeters.	Observed gain.	Gain per annum.
			millimeters.	*millimeters.*
Near shore off some large black lava rocks at Double Point, Pago Pago Harbor, exposed to the full force of the breakers at the western side of the harbor entrance. Bottom hard, broken, and rocky without sand or silt. Water constantly agitated and about a foot deep at lowest tides.	Brown colored *Acropora* (*Tylopora*) *leptocyathus* (Brook). This species thrives in the breakers.	July 5, 1918; 342 × 305 × 50 high.... Mar. 1, 1917; 249 × 184 × 4 high...	93 × 121 × 10 high..	70 × 90.7 × 7.5 high.
Do	*Acropora*	July 5, 1918; 148 × 121 × 66 high... Mar. 10, 1917; 47.5 × 42.5 × 35.5 high	100.5 × 78.5 × 30.5 high.....	75 × 59 × 23 high.
Do	*Acropora syringodes* (Brook) Fig. 51	July 5, 1918; 266 × 188 × 111 high.. Mar. 10, 1917; 80 × 53 × 32 high...	186 × 135 × 79 high.	139.5 × 101 × 59 high.
Do	*Pocillopora damicornis* var. *cespitosa* Dana.	July 5, 1918; 187 × 169 × 71 high... Mar. 10, 1917; 149 × 105 × 62 high.	38 × 64 × 9 high....	28.5 × 48 × 7 high.
Do	*Pocillopora damicornis* var. *cespitosa* Dana.	July 5, 1918; 192 × 133 × 75 high... Mar. 10, 1917; 99 × 79 × 58 high...	93 × 54 × 17 high...	70 × 40.5 × 13 high.
Do	*Pocillopora damicornis* var. *cespitosa* Dana.	July 1918; 147 × 152 × 71 high..... March 1917; 53 × 52 × 24 high.....	94 × 100 × 47 high..	70.5 × 75 × 35 high.
Do	*Pocillopora damicornis* var. *cespitosa* Dana.	July 1918; 123 × 59 × 59..... March 1917; 38 × 34.5 × 21.....	85 × 24.5 × 38 high..	64 × 18 × 28.5 high.
On the rocky floor of the reef-flat off Aua Village, about 440 feet from shore on the eastern side of Pago Pago Harbor in quiet water about 8 inches deep at lowest tides.	Massive, dome-shaped, olive - colored *Porites* aff. *P. lutea* M. Edw. and H. Fig. 52).	July 12, 1918; Circum. 52.5 inches.... April 6, 1917; Circum. 45.5 inches....	Gain in circumference 5.6 inches (142.2 mm.)	Gain in diameter per annum, 45 mm.
Do	*Pavona decussata* Dana...	July 12, 1918; 271 × 257 × 194 high. Apr. 6, 1917; 205 × 210 × 147 high..	66 × 47 × 47 high...	53 × 38 × 38 high.
Do	*Pavona decussata* Dana...	July 12, 1918; 292 × 232 × 196 high. Apr. 6, 1917; 241 × 178 × 136 high.	51 × 54 × 60 high...	37 × 40.5 × 45 high.
Aua reef-flat eastern side of Pago Pago Harbor, 600 feet from shore in water about 10 inches deep at lowest tides; bottom hard, broken coral with a little coarse sand; region is fairly quiet; water beyond the usual wash of the breakers.	*Favites abdita* (Ell. and Sol.).	July 17, 1918; 224 × 167 × 74 high.. Mar. 24, 1917; 183 × 151 × 46 high.	41 × 16 × 28 high...	31 × 12 × 21 high.
Do	*Leptastrea purpurea* (Dana), flat-incrusting colony.	July 19, 1918; 41 × 41..... March 24, 1917; 34 × 34.....	7 × 7.....	5 × 5
Do	*Pavona decussata* Dana...	July 18, 1918; 145 × 276 ocean top... Mar. 24, 1917; 130 × 249 ocean top.	15 × 27 across top....	11 × 20 across top.
Do	Nodular *Millepora*.....	July 22, 1918; 117 × 72 × 30 high... Mar. 24, 1917; 86 × 49 × 23 high...	31 × 23 × 7 high....	23 × 17 × 5
Corals growing on rocks on the Aua reef-flat, eastern side of Pago Pago Harbor, 750 feet from shore, just shoreward of the inner wash of the breakers, in water about a foot deep at lowest tides.	*Pocillopora damicornis* var. *cespitosa* Dana.	Aug. 4, 1918; 183 × 123 × 79 high... Apr. 12, 1917: 149× 8.15 × 49 high...	34 × 41.5 × 30 high.	25.5 × 31 × 22.5
Do	*Porites andrewsi* Vaughan, gray-green in color.	Aug. 4, 1918; 173 × 217 × 144 high.. Apr. 12, 1917; 142 × 118 × 106 high.	31 × 99 × 38 high...	23 × 74 × 28.5
Do	*Acropora samoensis* (Brook). brown with yellow tips.	Aug. 4, 1918; 251 × 164 × 69 high.. Apr. 17, 1917; 162 × 120 × 53 high.	99 × 24 × 16.....	74 × 18 × 12
Do	*Acropora damicornis* var. *gracilis* (Dana). Delicate branches, light brown with blue tips.	Aug. 4, 1918; 154 × 184 × 72..... Apr. 17, 1917; 154 × 118 × 46..... Cut off from lateral growth by crowding in a crevice.	0 × 66 × 26.....	2 × 49.5 × 19.5
Do	*Acropora teres* (Verrill). Olive-brown branches with blue-violet tips.	Aug. 4, 1918; 510 × 445 × 195 high. Apr. 17, 1917; 264 × 178 × 190 high. Prevented from growing upward by low-tide level.	246 × 267 × 5.....	184 × 200 × 4
Do	*Acropora teres* (Verrill)....	Aug. 4, 1918; 538 × 434 × 125 high. Apr. 17, 1917; 267 × 190 × 60 high..	271 × 244 × 65 high.	203 × 183 × 49 high.
Growing upon the vertical side of a large black lava rock about 200 feet from shore on the Aua reef-flat eastern side of Pago Pago Harbor; coral just under water at lowest tides.	*Acropora corymbosa* (Lamarck). Fig. 50.	July 17, 1918; 179 × 171 × 116 high. Apr. 9, 1917; 115 × 126 × 76.5 high.	64 × 45 × 39.5 high..	48.5 × 34 × 30 high.
Grown at a depth of 5 fathoms in Pago Pago Harbor in quiet silted water.	*Fungia* sp.....	July 6, 1920; 86 × 77 × 16..... Aug. 19, 1919; 70 × 61 × 13..... The weight changed from 64 to 85 grams; a gain of 21 grams.	16 × 16 × 3 mm..... Gain in weight 21 grams.	17 × 17 × 3

coral was dried in the sun and then weighed, in order to determine the weight of the stony substance, freed from animal matter and water. This method provided the means for calculating the weight of the stony substance as it was in 1917. The dimensions are stated in millimeters, the height being given last. Thus 10×20×15, means 10 × 20 mm. across the top × 15 mm. high.

These corals were collected at a depth of 1 to 2 fathoms on a bottom thickly covered with living coral in pure, agitated water, off the seaward edge of the reef on the eastern side of Pago Pago Harbor off Lepua Village. These corals were photographed, weighed, and measured and their bases set in concrete on concrete tiles which were secured by heavy spikes to the rocky bottom about 2

TABLE 4.—*Corals collected off Lepua Village, Pago Pago Harbor.*

Photo No., description, and name.	Dimensions on May 29, 1920, and on Sept. 3, 1919, in millimeters.	Weight on May 29, 1920, and Sept. 3, 1919.	Gain in dimensions in 9 months.	Gain in weight in 9 months.	Calculated gain in dimensions in one year.
		grams.	*millimeters.*	*grams.*	*millimeters.*
32 D. Brown - colored *Acropora hyacinthus* (Dana).	May 29, 1920; 176 × 138 × 136 high Sept. 3, 1919; 113.5 × 110 × 109 high.	May 1920; 850 Sept. 1919; 680	52.5 × 28 × 27 high.	170	70 × 37 × 33 high.
33 D. Greenish - brown, coarse-branched, *Pocillopora eydouxi* M. Ed. and Haime.	1920; 103 × 82 × 115..... 1919; 76.5 × 56 × 106.....	1920; 326 1919; 191	26.5 × 26 × 9.	135	35 × 34 × 12
35 D. Brown - colored *Acropora hyacinthus* (Dana) with pink tips to the branches.	1920; 247 × 214 × 99..... 1919; 116 × 119 × 88.....	1920; 1,162 1919; 496	131 × 95 × 11.	666	174 × 126 × 16
36 D. *Acropora cymbicyathus* (Brook). Brown-colored *Acropora*.	1920; 199 × 168 × 90..... 1919; 180 × 106 × 84.....	1920; 652 1919; 447	19 × 62 × 6...	205	25 × 82 × 8
40 D. *Millepora truncata* Dana. Olive - brown *Millepora* with greenish-yellow tips to its coarse branches.	1920; 107 × 49 × 135..... 1919; 94 × 33 × 134.....	1920; 468 1919; 439	13 × 16 × 1...	29	17 × 21 × 1
41 D. *Coscinarea columna* (Dana)	1920; 57 × 82 × 110..... 1919; 55 × 84 × 97.....	1920; 503 1919; 453	2 × − 2 × 13.	50	3 × − 3 × 17
42 D. *Pocillopora eydouxi* M. E. and H. Coarse-branched, greenish-brown *Pocillopora*.	1920; 153 × 115 × 124..... 1919; 136 × 87 × 126.....	1920; 836 1919; 574	17 × 28 × $-^{2}$.	262	23 × 37 × $-^{3}$
43 D. Light-brown, fine-branched *Acropora*.	1920; 166 × 148 × 121..... 1919; 113 × 87 × 115.....	1920; 489 1919; 213	53 × 61 × 6...	276	70 × 81 × 8
44 D. Olive - brown *Millepora* with yellow-green tips. *Millepora truncata* Dana.	1920; 49 × 31 × 95..... 1919; 45.5 × 30 × 94.....	1920; 218 1919; 205	3.5 × 1 × 1...	13	5 × 1 × 1
45 D. *Pocillopora damicornis* var. *cespitosa* Dana (*brevicornis* facies). Dark-brown *Pocillopora*.	1920; 110 × 141 × 82..... 1919; 87 × 116 × 73.....	1920; 340 1919; 241	23 × 25 × 9...	99	31 × 33 × 12
47 D. *Acropora tutuilensis*, Hoffmeister. Brownish-green, coarse, long-branched.	1920; 204 × 112 × 160..... 1919; 138 × 34 × 151.....	1920; 369 1919; 170	66 × 78 × 9...	199	88 × 104 × 12
49 D. *Pocillopora brevicornis* Lamarck. Olive-brown.	1920; 113 × 104 × 73..... 1919; 94.5 × 87.5 × 57.....	1920; 311 1919; 240	18.5 × 16.5 × 16	71	25 × 22 × 21
50 D. Brown - colored. *Acropora hyacinthus* (Dana).	1920; 128 × 178 × 97..... 1919; 72 × 109 × 78.....	1920; 219 1919; 128.	56 × 69 × 19..	91	74 × 92 × 25
51 D. *Acropora valida* (Dana). Brown - colored, short-branched.	1920; 111 × 120 × 98..... 1921; 74 × 79 × 63.5.....	1920; 220 1919; 50	37 × 41 × 34.5.	170	49 × 55 × 46

fathoms deep, near the place wherein the corals were collected, in order to withstand the heavy surge of the breakers over them.

The average dimensions of these seven corals on July 27, 1919, were 109 × 119 × 43 mm. high, and it was found that specimens of this size weigh 461 grams. These corals were remeasured and weighed on June 3, 1920, and found to have gained on the average 91 grams in weight. These corals were of about average size for their species when growing on the edges of reefs.

TABLE 5.—*Growth-rate of seven specimens of Acropora (Tylopora) leptocyathus (Brook) growing naturally on breaker-washed edge of a reef patch off Aua Village, Pago Pago Harbor, Samoa.*

Remarks.	Dimensions, July 27, 1919 and June 3, 1920, in millimeters.	Observed gain in dimensions between July 27, 1919, and June 3, 1920.	Weight, June 3, 1920.	Calculated increase in dimensions in one year.
		millimeters.	*grams.*	*millimeters.*
About one-third dead in 1920...	1920: 104 × 103 × 45 high 1919: 82 × 84 × 53 high	22 × 19 × 8 high	539	26 × 23 × 8 high
Alive and flourishing, 1920.....	1920: 175 × 150 × 48..... 1919: 137 × 135 × 48.....	38 × 15 × 0.....	964	46 × 18 × 0
Dead, 1920.....	1920: 97 × 94 × 46..... 1919: 90 × 90 × 46.....	7 × 4 × 0.....	240	8 × 5 × 0
Alive, 1920.....	1920: 199 × 156 × 41..... 1919: 148 × 126 × 40.....	51 × 30 × 1.....	482	61 × 36 × 1
Dead on one side, 1920.....	1920: 124 × 99 × 33..... 1919: 109 × 92 × 33.....	15 × 7 × 0.....	666	18 × 8 × 0
Alive, 1920.....	1920: 181 × 157 × 40..... 1919: 124 × 118 × 35.....	57 × 39 × 5.....	822	68 × 47 × 6
Alive, 1920.....	1920: 174 × 146 × 46..... 1919: 145 × 120 × 46.....	29 × 26 × 0.....	893	35 × 31 × 0
	Average dimensions in 1919, 119 × 109 × 43 mm. high. Average in 1920, 151 × 129 × 43.	Average gain in dimensions from July 27, 1919, to June 3, 1920, 32 × 20 × 0 mm.	Average weight on June 3, 1920, 658 grams.	Average gain in one year, 36 × 24 × 0 mm.

These corals grew about 400 feet from shore in water about a foot deep at lowest tide. They were weighed (ounces avoirdupois) and measured on August 1, 1918, and then each coral was fastened by an iron spike to the rocky floor of the reef-flat, the spikes being driven through the dead central area of the coral-head. (See figure A, plate I.) Two small galvanized-iron nails were driven into the sides of each coral to mark a diameter. The corals were weighed with these side-nails in place but without the central spike. Massive *Porites* heads flourish in the region in which these corals were grown, and all were collected within a few feet of the place wherein they were grown from August 1, 1918, to August 23, 1919.

The coral-heads described in table 7 grew in quiet water about 1 to 4 feet deep at lowest tide. They were dead about at low-tide level and were growing laterally. They were from 150 to 360 feet from shore. At Fagaalu and Muaivuso the bottom was covered with calcareous sand and the corals grew above it, but at Utelei the bottom is rocky. These corals are in protected places away from the breakers.

Table 8 describes corals collected on the Aua Reef-flat. Each coral was sawed into two approximately equal halves marked "S" and "D." One of these

TABLE 6.—*Growth of massive Porites heads allied to P. lutea M. Edw. and H., from off Fagaalu, on the west side of Pago Pago Harbor, Samoa.*

Date.	Circumference.	Diameters.	Weight.	Observed gain.			Calculated annual growth.		
				Gain in circumference.	Average gain in diameter.	Gain in weight, oz. avoirdupois.	Circumference.	Diameter.	Weight.
	mm.	*mm.*	*ounces.*	*mm.*	*mm.*		*mm.*	*mm.*	*ounces.*
Aug. 1, 1918....	870	270 × 276	326	90	36	114	85	34	107
Aug. 23, 1919....	960	306 × 313	440						
Aug. 1, 1918....	902	276	226	132	35	130	124	33	122
Aug. 23, 1919....	1,034	311	356						
Aug. 1, 1918....	1,448	472 × 425	.....	105	40	.....	99	38	.....
Aug. 23, 1919....	1,553	509 × 469	.....						
Aug. 1, 1918....	.....	88 × 62	.....	.....	38	.....	.....	36	.....
Aug. 23, 1919....	.....	126 × 101	.....						
Aug. 1, 1918....	1,400	431 × 435	.....	70	44	.....	66	41	.....
Aug. 23, 1919....	1,470	477 × 477	.....						
Aug. 1, 1918....	629	174 × 216	106	86	45	94	81	42	89
Aug. 23, 1919....	715	215 × 256	200						
Aug. 1, 1911....	1,130	360 × 355	334	96	35	146	90	33	85
Aug. 23, 1919....	1,226	391 × 393	480						
Apr. 16, 1917....	648	.....	168	171	.....	85	137	43	78
July 8, 1918....	819	.....	274						

Average initial circumference, 1,068 mm.; average initial diameter, 339 mm.; average gain in diameter in 12 months, 37.5 mm.; average gain in weight in 12 months, 96 oz. av. or 2,722 grams.

halves marked "S" was embedded in concrete and kept from July 25, 1919, to June 12, 1920, in constantly agitated pure water, in a tide-pool near the seaward margin of a reef-patch off Aua Village, Pago Pago Harbor. The water in this tide-pool was about a foot deep at low tide and was constantly in motion, due to the surge of the sea. The other half of each coral, marked "D," was embedded in concrete on a concrete base, and lowered into quiet water off the northern edge of the same reef-patch. Nos. 1 D to 12 D were grown in water 7 fathoms deep, and Nos. 13 D to 24 D in water 8.5 fathoms deep The bottom was hard and rocky and no current could be detected by an Ekman meter in this deep water. Thus one half, "S," of each coral was grown in shallow, agitated water, while the other half, "D," was grown in quiet, deep water. The reef-patch upon which and off which this experiment was made is off Aua Village and is marked "uncov. at L. W." on U. S. Hydrographic Chart No. 2563 of Pago Pago Harbor.

All of the *Acropora* placed in deep water were killed at once by the silt. The *Porites*, *Psammocora*, *Pocillopora*, and *Pavona* generally survived in the quiet deep water, but usually produced abnormally slender stems, whereas the halves of the corals grown in the agitated shallow water usually produced short, thick, compact stems.

The *Acropora leptocyathus* grown in shallow agitated water was in its natural habitat, but all other corals were in abnormal habitats.

TABLE 7.—*Annual gain in diameter of large, flat-topped, massive Porites heads (allied to P. lutea M. Edw. and H., growing on the shallow reef-flats off Fagaalu and Utelei, on the west side of Pago Pago Harbor, Samoa, and off Muaivuso Village, Viti Levu, Fiji.*

Description of the *Porites* head.	Gain in diameter in 12 months.
An elliptical *Porites* about 150 feet from shore off Utelei Village. Dimensions in millimeters Apr. 16, 1917: circumference 3,395 mm., diameters 951 × 1,134 mm.	49 mm. in 1917–1918 33 mm. in 1918–1919 Dead, 1920, turned over on side.
Nearly circular, isolated, flat-topped *Porites* about 200 feet from shore of Utelei. Dimensions in millimeters, Apr. 16, 1917: circumference 3,054 mm., diameter 972 mm.	18 mm. in 1917–1918 43 mm. in 1918–1919 6 mm. in 1919–1920
Oval *Porites* about 300 feet from shore off Utelei. Dimensions on Apr. 16, 1917: circumference 2018 mm. diameters 677 × 555 mm.	24 mm. in 1917–1918 9 mm. in 1918–1919 30 mm. in 1919–1920
Circular *Porites* head in water about 3 feet deep at low tide, about 300 feet offshore on the reef-flat off Fagaalu Village, Apr. 16, 1917: circumference 6,404 mm.	37 mm. in 1917–1918 0 mm. in 1918–1919 54 mm. in 1919–1920
Circular *Porites* head in water about 4 feet deep at low tide off Fagaalu Village, about 32 5feet from shore, Apr. 16, 1917: circumference 1,500 mm.	38 mm. in 1917–1918
Very large, isolated, nearly circular, yellow-colored *Porites* head on the Utelei reef-flat in water about 2 feet deep at low tide. Dimensions on Aug. 25, 1919: circumference (29.1 feet) 8,870 mm., diameter 2,823 mm.	35 mm. in 1919–1920
Cleft near the center of the top of a large *Porites* head off Fagaalu Village. The sides of this cleft are growing toward one another, tending to close the opening. The sides were 296.5 mm. apart on Apr. 14, 1917.	27 mm. 1917–1918 26 mm. 1918–1919 23 mm. 1919–1920

The following gives the annual gain in diameter of three large massive *Porites* heads allied to *P. lutea* (M. Edw. and H.), southwest of the village of Muaivuso, west of Suva Harbor, Viti Levu Island, Fiji, about 120 yards from shore. These heads were dead above at low-tide level, and were growing laterally. The first measurments were made September 2, 1918, and the last April 18, 1920.

Description of the *Porites* head.	Gain in diameter in 12 months.
Brown-colored, nearly circular *Porites*, growing on a hard bottom covered with some sand and about a foot deep at low tide. Dimensions on Sept. 2, 1918: circumference 8,156 mm. (26.76 feet), diameter 2,596 mm. On April 18, 1920 the dimensions were: circumference 8,321 mm. (27.3 feet), and diameter 2,654 mm.	36 millimeters.
Large brown-colored *Porites* head a few feet south of the one mentioned above. This head was nearly circular in contour, and was dead at low-tide level above, and growing laterally. Dimensions on Sept. 2, 1918: circumference 7,608 mm. (24.76 feet) or 2,421 mm. diameter. On Apr. 18, 1920, the dimensions were: circumference 7,740 mm. (25.39 feet) diameter 2,463 mm.	26 millimeters.
Yellow-colored massive *Porites* head nearly circular in outline. Dead above at low-tide level and growing laterally. About 300 feet S. by W. from the two large brown heads off Mauivuso Village. Dimensions on Sept. 2, 1918: circumference 4,817 mm. (15.77 feet); diameter 1,530 mm.	23 millimeters.
Average gain in diameter per annum of these *Porites* heads from Fagaalu, Utelei, and Muaivuso, 28 mm.	
Average initial circumference 5,091 mm.; average initial diameter 1,620 mm.	

TABLE 8.

Photo. No. and description and name of coral.	Dimensions on July 25, 1919, and June 12, 1920, in millimeters.	Weight on July 25, 1919, and June 12, 1920.	Observed gain in dimension in 10½ months.	Observed gain in weight in 10½ months.
		grams.	*millimeters.*	*grams.*
1 S. *Psammocora contigua* Esper., olive-colored *Psammocora*; the fragile stems of this coral were broken in the half grown in agitated shallow water.	1920; 67 × 32 × 38 high..... 1919; 81 × 58 × 55.....	.....	—14 × —26 × —17; stems all broken by the agitated water; the surviving stems were all short, thickened, and compact.	
1 D. *Psammocora contigua* Esper., olive-colored *Psammocora.*	1920; 97 × 59 × 53, high... 1919; 71 × 59 × 47.....	.....	20 × 0 × 6; the new branches are more slender than the old ones.	
2 S. *Pocillopora damicornis* var. *cespitosa* Dana.	Gone, 1920.....			
2 D. *Pocillopora damicornis* var. *cespitosa* Dana.	1920; 92 × 82 × 66..... 1919; 81 × 79 × 60.....	1920; 85 1919; 71	11 × 3 × 6; new branches more slender than the old ones.	14
3 S. *Acropora* (*Tylopora*) *leptocyathus* (Brook).	1920; 133 × 115 × 81..... 1919; 93 × 64 × 58.....	1920; 595 1919; 297	40 × 51 × 23.....	298
3 D. ....Do.....	Dead, made no growth.....			
4 S. *Acropora fructicosa* (Brook).....	1920; 161 × 150 × 111..... 1919; 156 × 115 × 75.....	1920; 879 1919; 553	5 × 35 × 36.....	326
4 D, ...Do.....	Dead, made no growth.....			
5 S. *Psammocora contigua* var. *maldivensis* Gardiner, brown-colored *Psammocora.*	1920; 82 × 64 × 41..... 1919; 81 × 63 × 64.....	1920; 92 1919; 113	1 × 1 × —23.....	21 loss
5 D. ....Do.....	1920; 91 × 71 × 73..... 1919; 79 × 66 × 65.....	1920; 128 1919; 111	12 × 5 × 8.....	17
6 S & 6 D. *Porites lutea M. Edw. and H*	Dead, made no growth.....			
7 S. Drab-colored *Porites andrewsi* Vaughan.	1920; 152 × 101 × 108.... 1919; 152 × 95 × 94.....	1920; 312 1919; 213	0 × 6 × 14.....	99
7 D. ....Do.....	Dead, made a slight growth before dying.....			
8 S. Light-brown *Acropora* (*Tylopora*) *leptocyathus* (Brook).	1920; 122 × 83 × 58..... 1919; 110 × 80 × 58.....	1920; 482 1919; 241	12 × 3 × 0.....	241
8 D. ....Do.....	Died without growing.....			
9 S. *Acropora massawensis* von Mar.....	Only a small part living. The remainder dead and corroded in 1920.....			
9 D. ....Do.....	Died, without growing.....			
10 S. *Pocillopora damicornis* var. *cespitosa* Dana.	1920; 99 × 83 × 64..... 1919; 118 × 83 × 46.....	1920; 198 1919; 177	—19 × 0 × 18.....	21
10 D. ....Do.....	1920; 130 × 107 × 67..... 1919; 128 × 104 × 64 half dead.....	1920; 269 1919; 269	2 × 3 × 3.....	0
11 S. Olive-green colored *Porites andrewsi* Vaughan.	1920; 139 × 121 × 106..... 1919; 121 × 111 × 81.....	1920; 405 1919; 262	18 × 10 × 25.....	143
11 D. ....Do.....	1920; 119 × 68 × 104..... 1919; 116 × 69 × 71.....	1920; 177 1919; 170	3 × —1 × 33.....	7
12 S & 12 D. *Acropora* sp. aff. *A. samoensis* (Brook).	12 S gone in 1920..... 12 D died without growing.			
13 S & 13 D. *Acropora* (*Tylopora*) *samoensis* (Brook).	13 S nearly all dead..... 13 D died without growing.			
14 S. *Acropora hebes* (Dana); brown long-stemmed *Acropora.*	1920; 107 × 54 × 87 ..... 1919; 110 × 71 × 105.....	1920; 184 1919; 106	—3 × —17 × —18; stems much thickened.	78
14 D. ....Do.....	Died without growing.....			

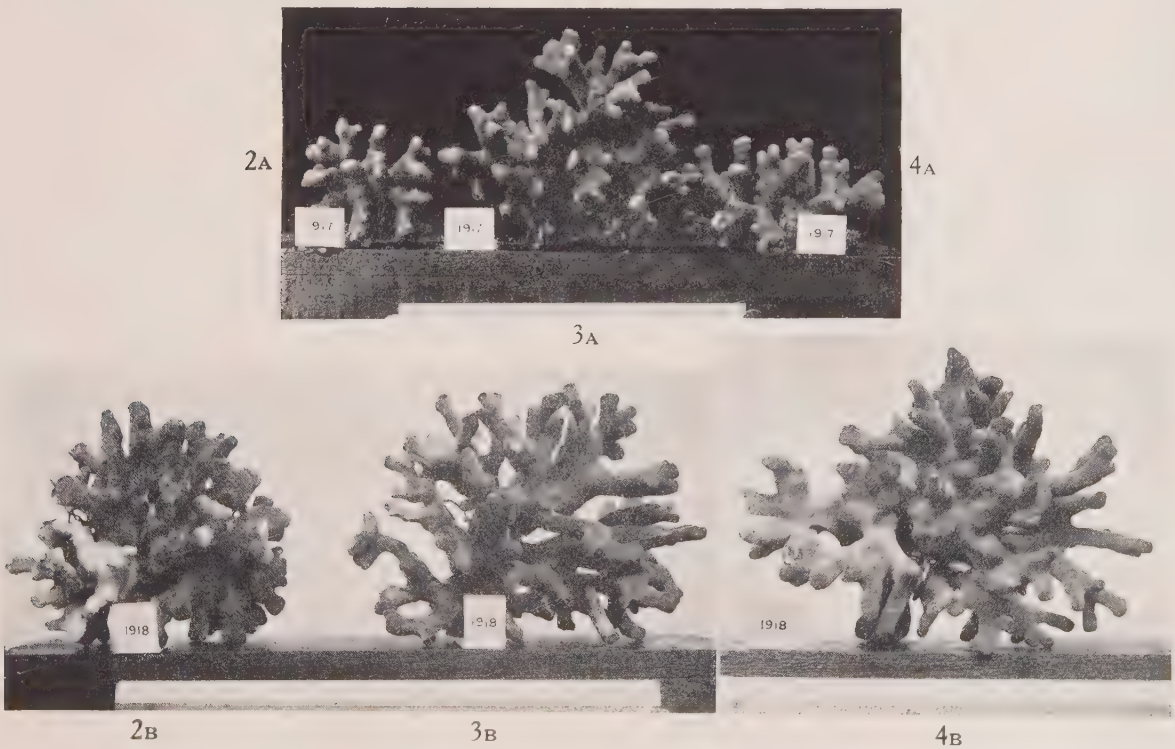
TABLE 8.—Continued.

Photo. No. and description and name of coral.	Dimensions on July 25, 1919, and June 12, 1920, in millimeters.	Weight on July 25, 1919, and June 12, 1920.	Observed gain in dimension in 10½ months.	Observed gain in weight in 10½ months.
		grams.	*millimeters.*	*grams.*
15 S. *Pavona divaricata* Lamarck; light-brown *Pavona.*	1920; 92 × 43 × 48..... 1919; 75 × 36 × 32.....	1920; 149 1919; 99	17 × 7 × 16; fronds very compact and thick set.	50
15 D. ....Do.....	1920; 101 × 63 × 58..... 1919; 104 × 62 × 36.....	1920; 170 1919; 156	7 × 1 × 22.....	14
16 S & 16 D. Dark-brown *Porites andrewsi* Vaughan.	Both half dead.....			
17 S. *Psammocora contigua* var. *maldivensis* Gardner; light green *Psammocora*..	1920; 96 × 60 × 45..... 1919; 97 × 53 × 47.....	1920; 136 1919; 106	—1 × 7 × —2; short stumpy stems.	30
17 D. ....Do.....	1920; 89 × 58 × 56..... 1919; 86 × 54 × 47.....	.....	3 × 4 × 9; new branches slender.	
18 S. Massive *Porites*, *P. lutea* var. *haddoni* Vaughan.	1920; 94 × 74 × 78..... 1919; 78 × 68 × 62.....	1920; 404 1919; 255	16 × 6 × 16.....	149
18 D. ....Do.....	About half dead in 1920....			
19 S & 19 D. Massive *Porites*, *P. lutea* var. *haddoni* Vaughan.	Both about half dead in 1920; made slight growth.			
20 S & 20 D. *Pocillopora brevicornis* (Lamarck) brown-colored *Pocillopora.*	20 S only about ¼ of the coral alive in 1920; 20 D died without growing.			
21 S. Dark-brown *Pocillopora damicornis* var. *cespitosa* Dana.	1920; 67 × 54 × 44..... 1919; 108 × 40 × 58.....	1920; 57 1919; 100	—41 × 14 × —18; stems short and compact.	—43
21 D. ....Do.....	1920; 122 × 79 × 74..... 1919; 102 × 64 × 56.....	1920; 127 1919; 113	20 × 15 × 18; new stems very slender.	14
22 S & 22 D. Olive-colored massive *Porites* aff. *P. lutea* var. *haddoni* Vaughan.	22 S gone in 1920; 22 D alive, but made very little growth, increase in diameter only 2 mm.			
23 S. Dark-brown *Porites andrewsi* Vaughan..	1920; 112 × 85 × 69..... 1919; 107 × 81 × 60.....	1920; 227 1919; 186	5 × 4 × 9.....	41
23 D. ....Do.....	Died without growing.....			
24 S. Light-green *Porites andrewsi* Vaughan...	Gone 1920.....			
24 D. ....Do.....	1920; 156 × 124 × 129..... 1919; 128 × 116 × 82.....	1920; 326 1919; 256	28 × 8 × 47; new branches very slender in comparison with the old ones	70

A.—Seven small heads of *Porites* aff. *P. Lutea* grown off Fagaalu, Pago Pago Harbor, from August 1, 1918, to August 23, 1919. (See table 5).

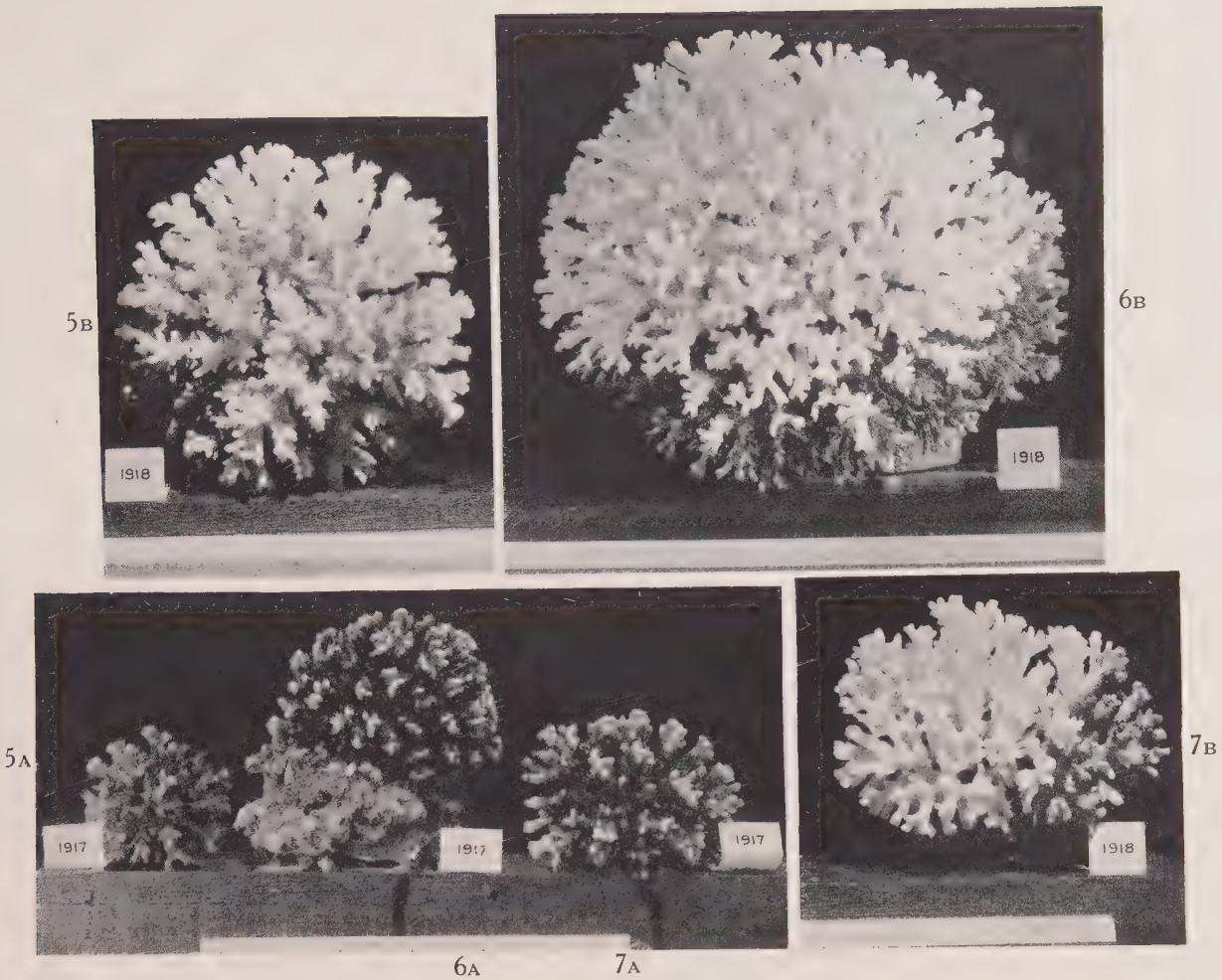
B.—Edge of reef patch off Aua Village, Pago Pago Harbor, in a calm at low tide, showing overhanging edge of reef and clusters of *Acropora leptocyathus* growing on the lithothamnium ridge of the reef-edge. The large bracket-like vase-shaped coral in the middle distance is *Acropora hyacinthus*, a coral characteristic of pure agitated water.

Fig. 1.—Acropora hyacinthus (Dana).

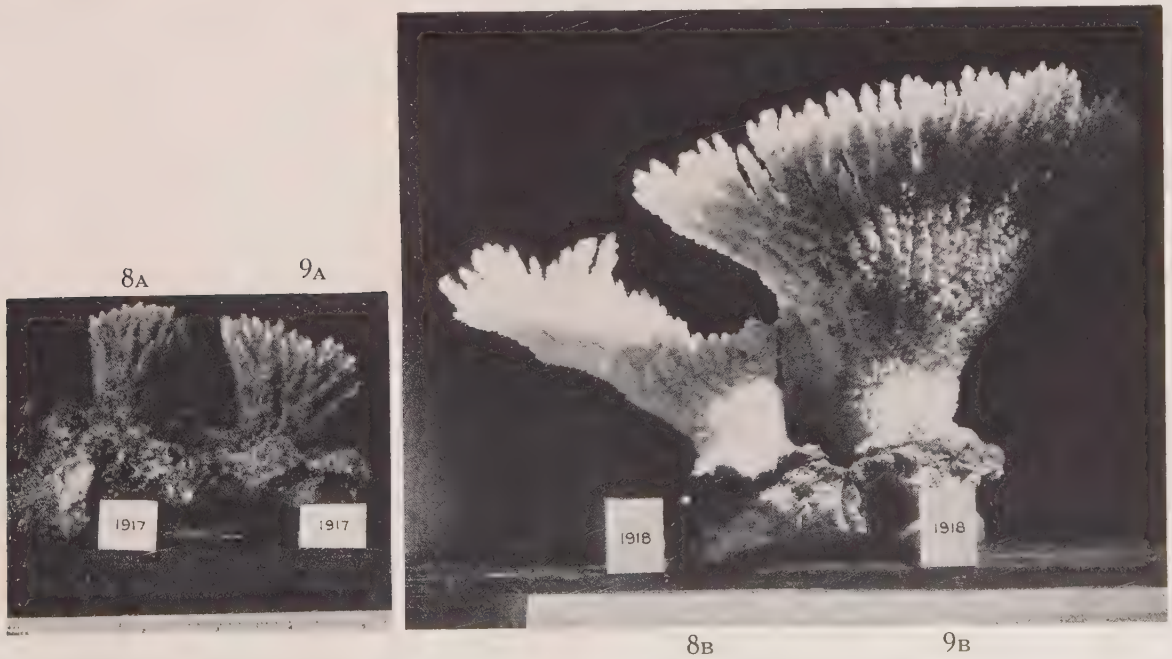


Figs. 2 to 4.—Porites andrewsi Vaughan.

NOTE.—In these plates, A represents the coral when it was taken out of the water for a short time, photographed, embedded in concrete, and returned to the water; the B of the same number shows the same coral at a later date when it was collected for the last time. In all cases, D represents a colony, or half of a colony, which was grown in deep water; S represents a colony, or half of a colony, which was grown in shallow water. This is thoroughly explained on pages 54, 55, and 69. J. E. H.



Figs. 5 to 7.—Pocillopora damicornis var. cespitosa Dana.



Figs. 8, 9.—Acropora hyacinthus (Dana).

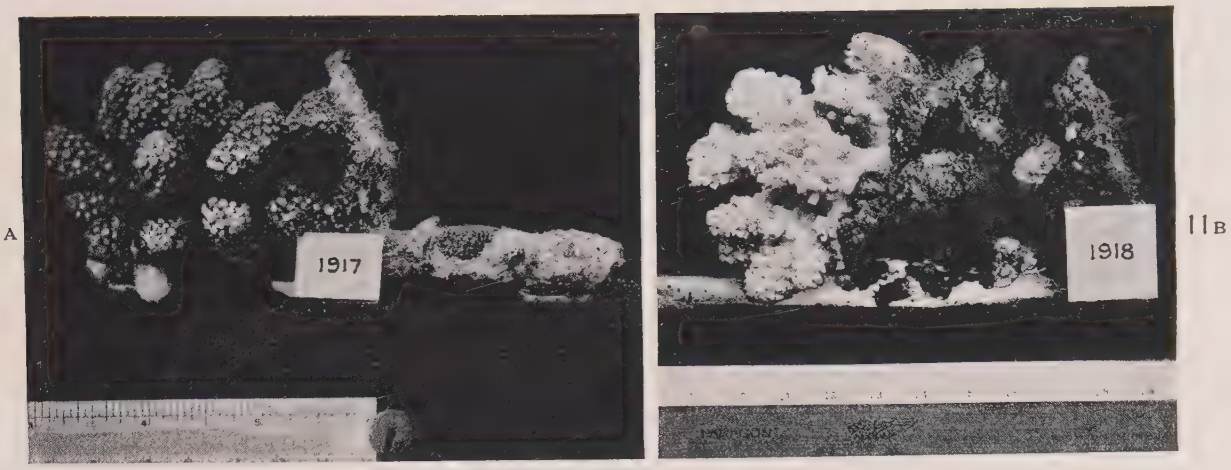


Fig. 11.—Acropora aff. A. humilis (Dana).

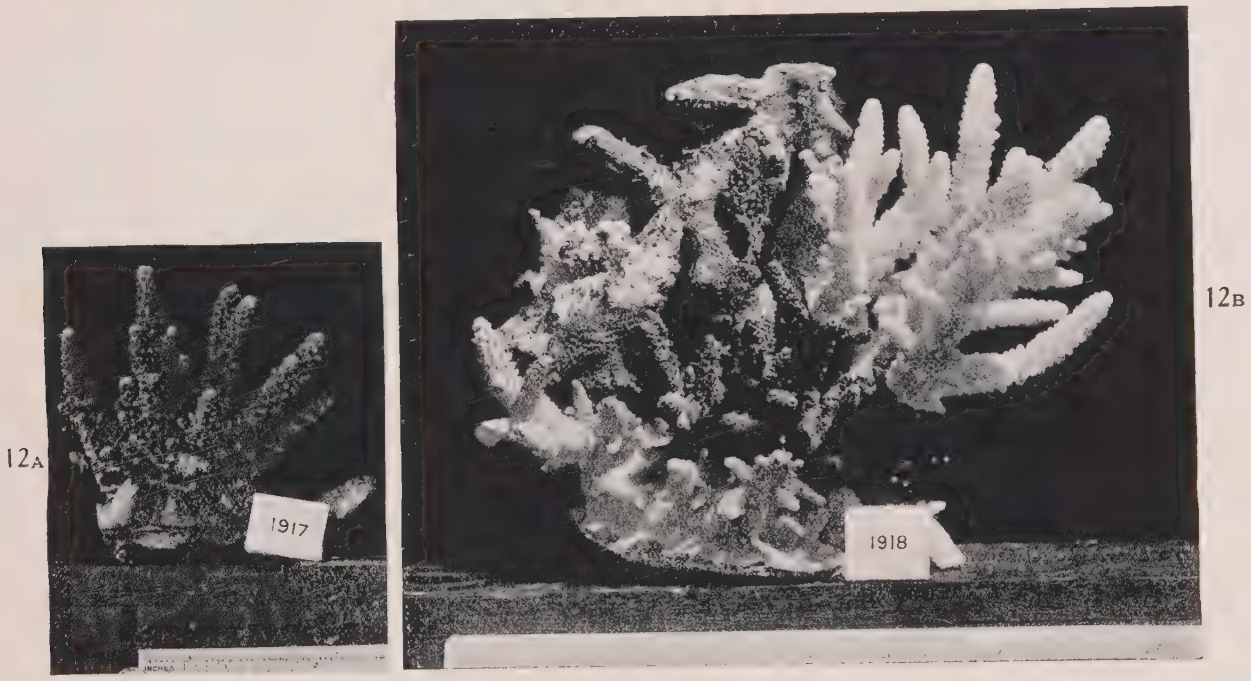


Fig. 12.—Acropora (Tylopora) samoensis (Brook).

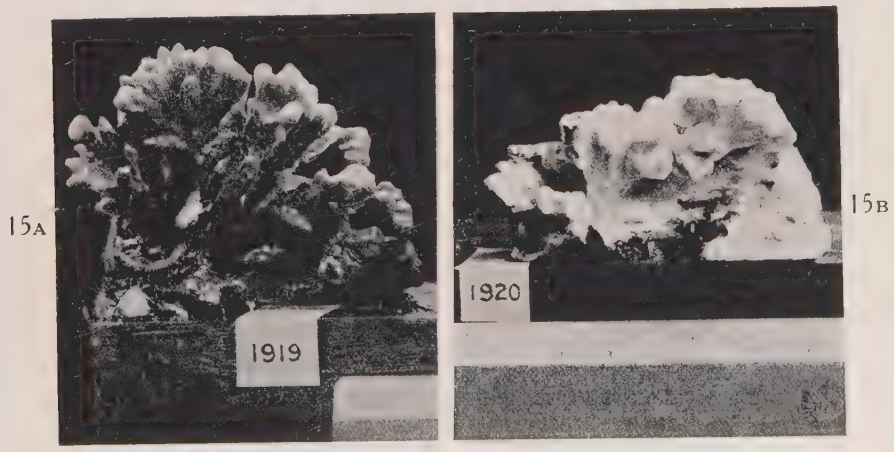
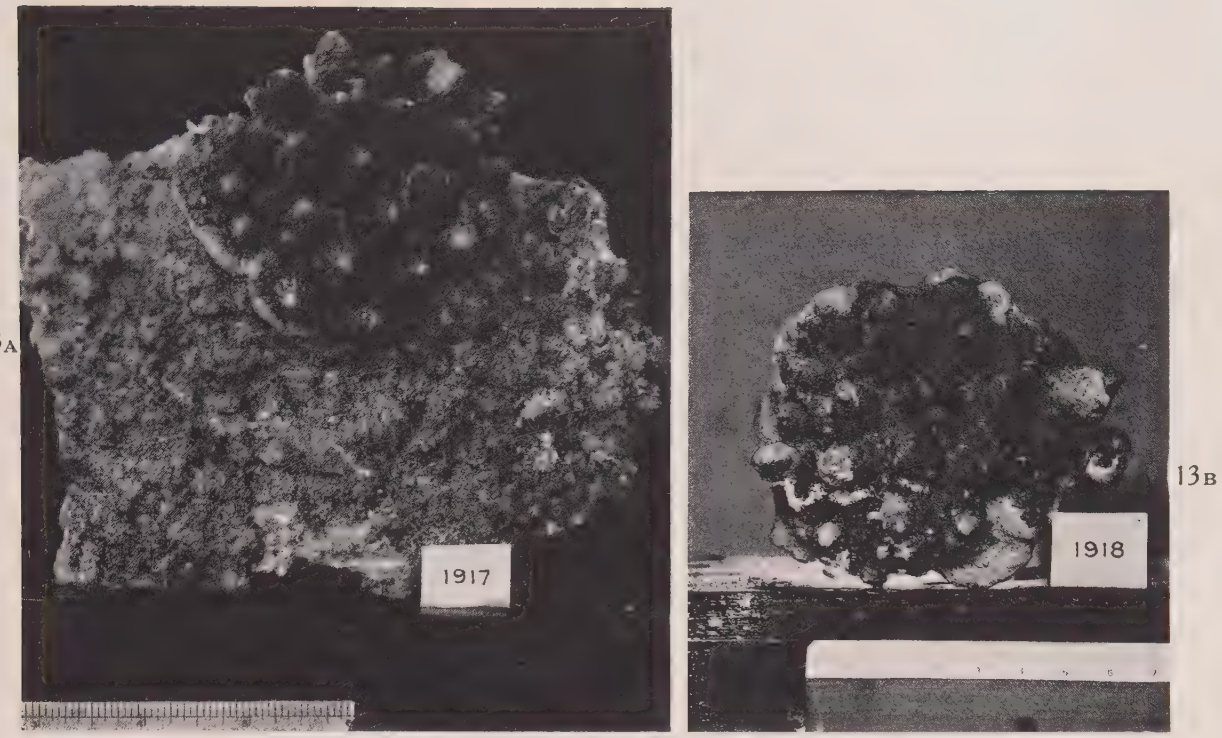
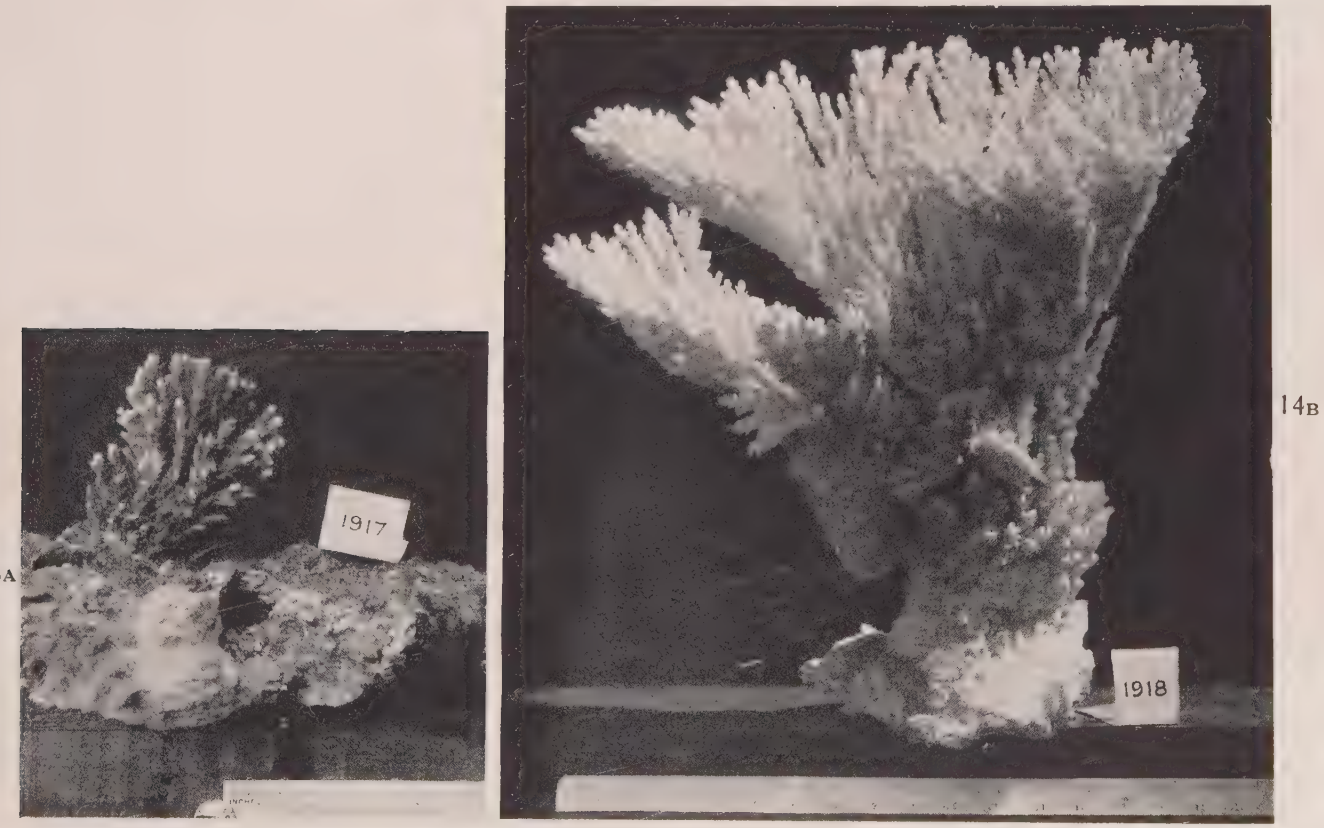


Fig. 15.—Pavona divaricata Lamarck.



13A 13B

Fig. 13.—Acropora (Tylopora) leptocyathus (Brook).



14A 14B

Fig. 14.—Acropora hyacinthus (Dana).

16A

16B

Fig. 16.—Acropora (Tylopora) samoensis (Brook).

19B Fig. 19.—Acropora teres (Verrill). 19A

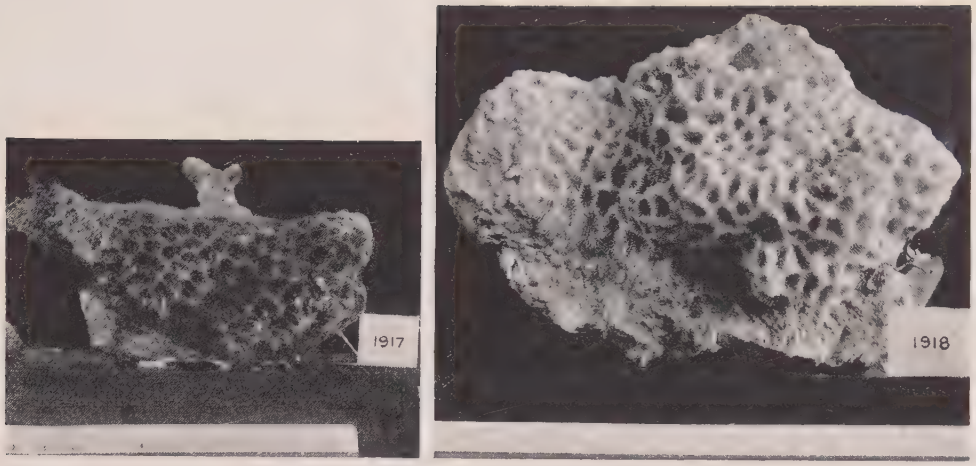


Fig. 20.—Favites abdita (Ellis and Solander).

Fig. 17.—Porites andrewsi Vaughan.

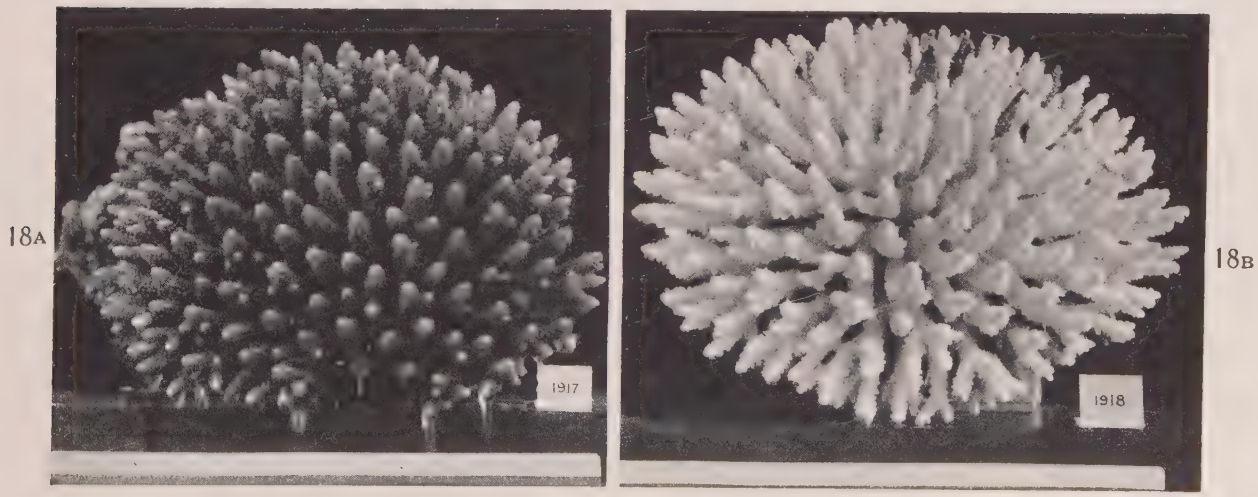
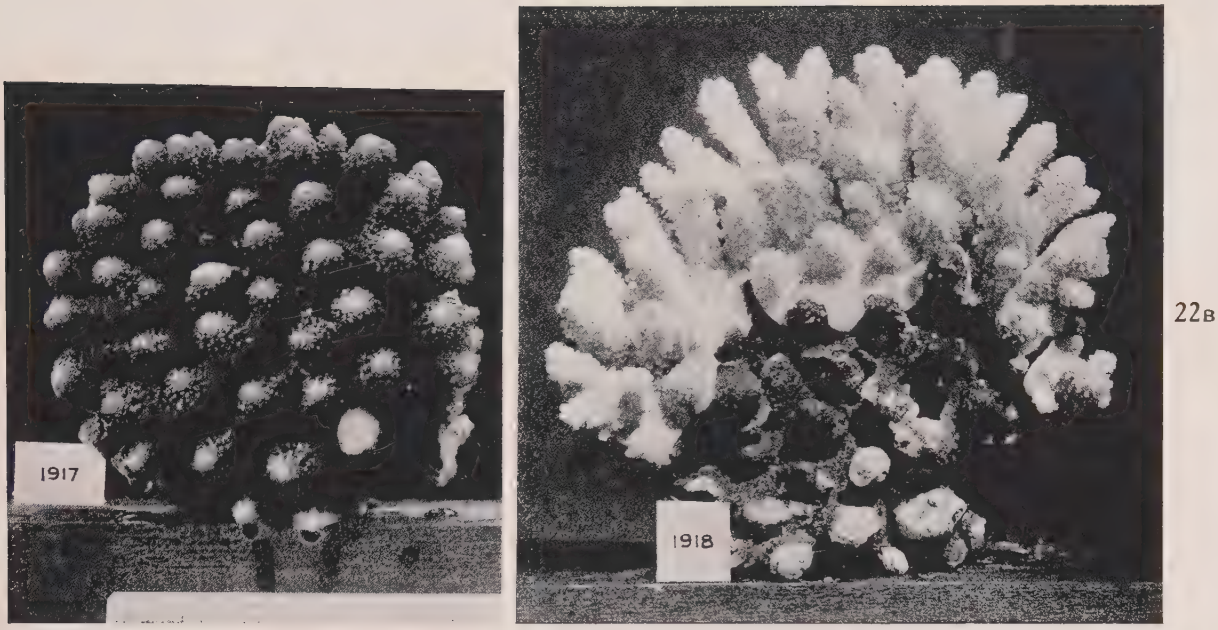


Fig. 18.—Acropora (Polystachis) cymbicyathus (Brook).

22A



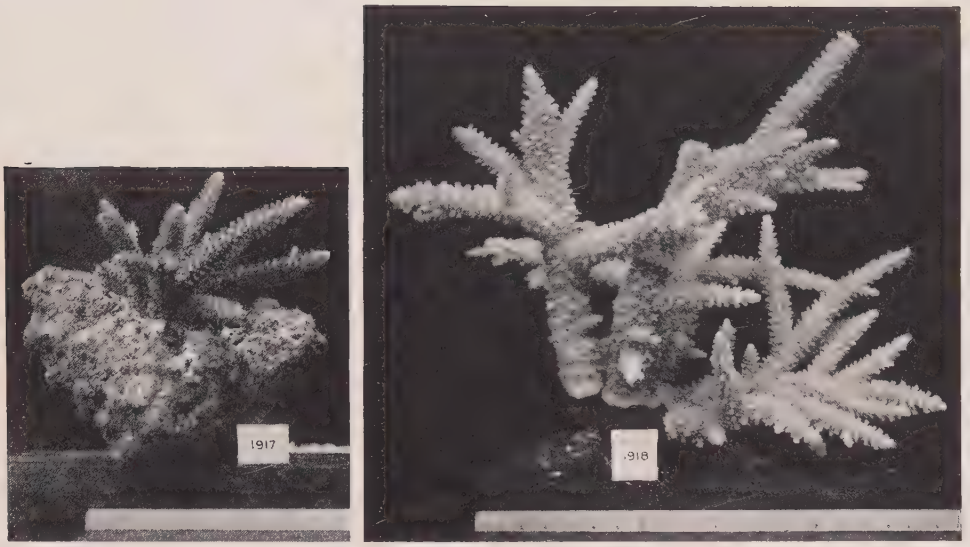
22B

Fig. 22.—Acropora (Tylopora) leptocyathus (Brook).

23A

23B

Fig. 23.—Pavona decussata Dana.



24A 24B

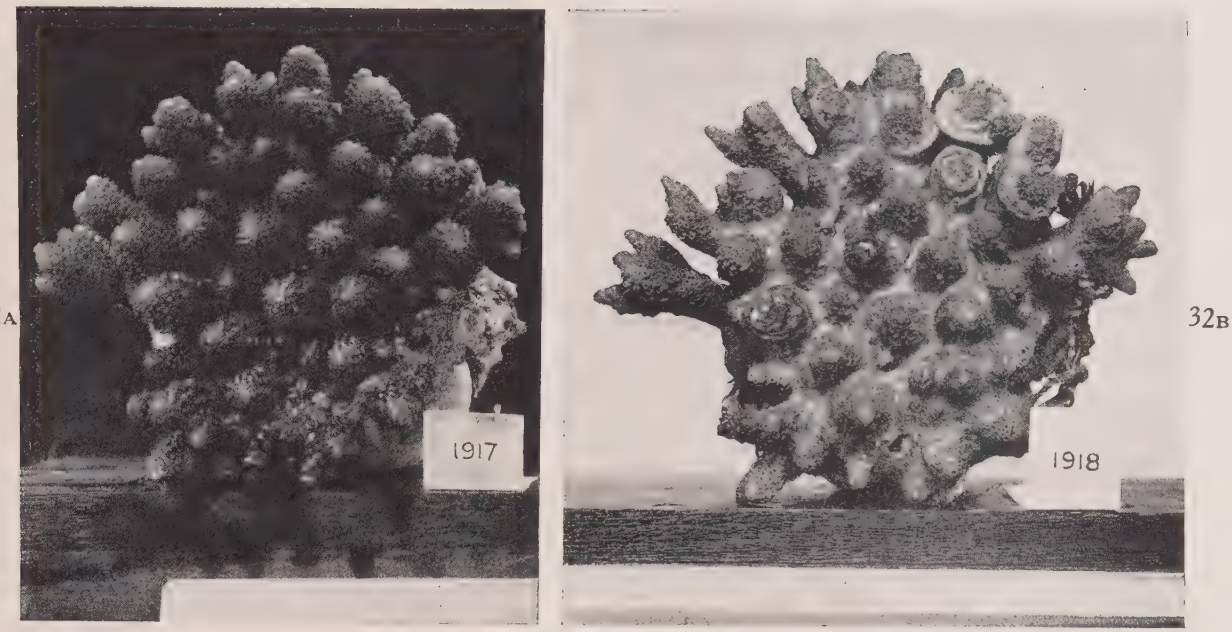
Fig. 24.—Acropora vanderhorsti Hoffmeister.

28A 28B

Fig. 28.—Pocillopora damicornis var. cespitosa Dana (*brevicornis* facies).

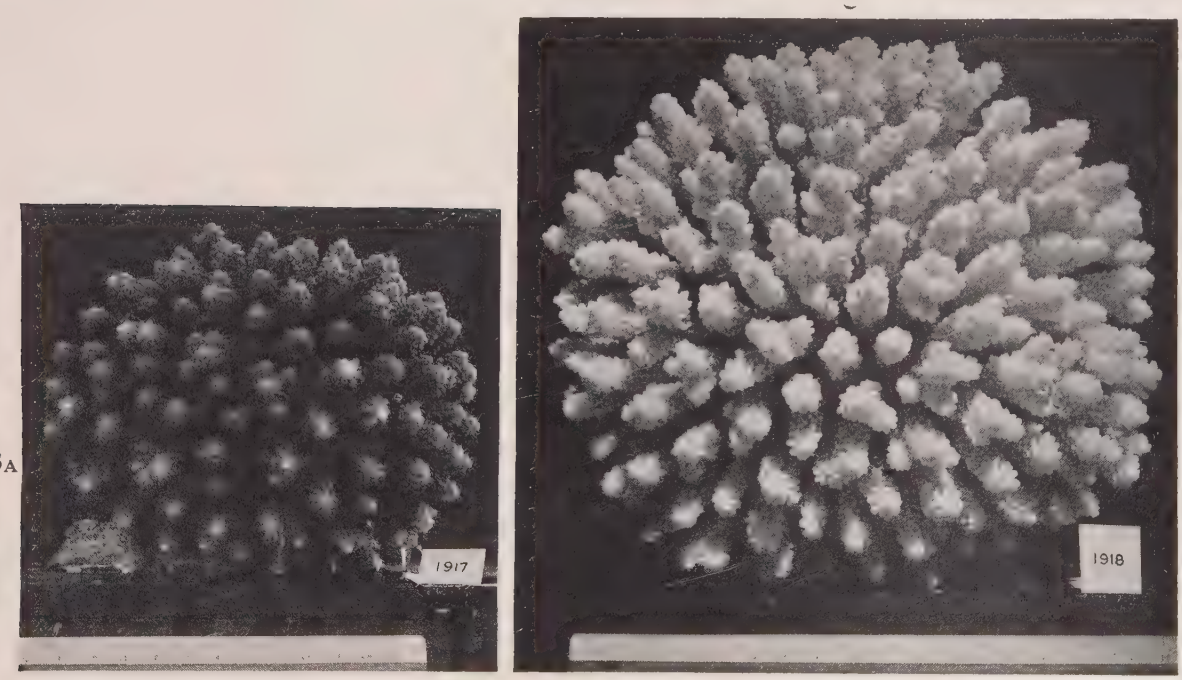
Fig. 29.—Acropora corymbosa (Lamarck).

Fig. 30.—Pocillopora eydouxi M. Ed. and H.



32A 32B

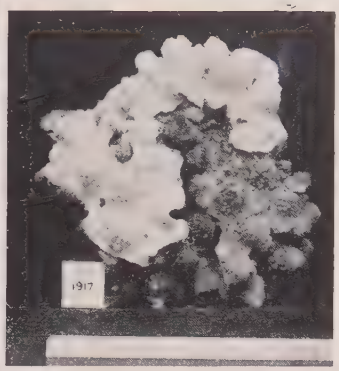
Fig. 32.—Acropora (Tylopora) leptocyathus (Brook).



33A 33B

Fig. 33.—Acropora (Conocyathus) valida (Dana).

34



35

Fig. 34.—Acropora hyacinthus (Dana).
Fig. 35.—Acropora (Tylopora) leptocyathus (Brook).

36A

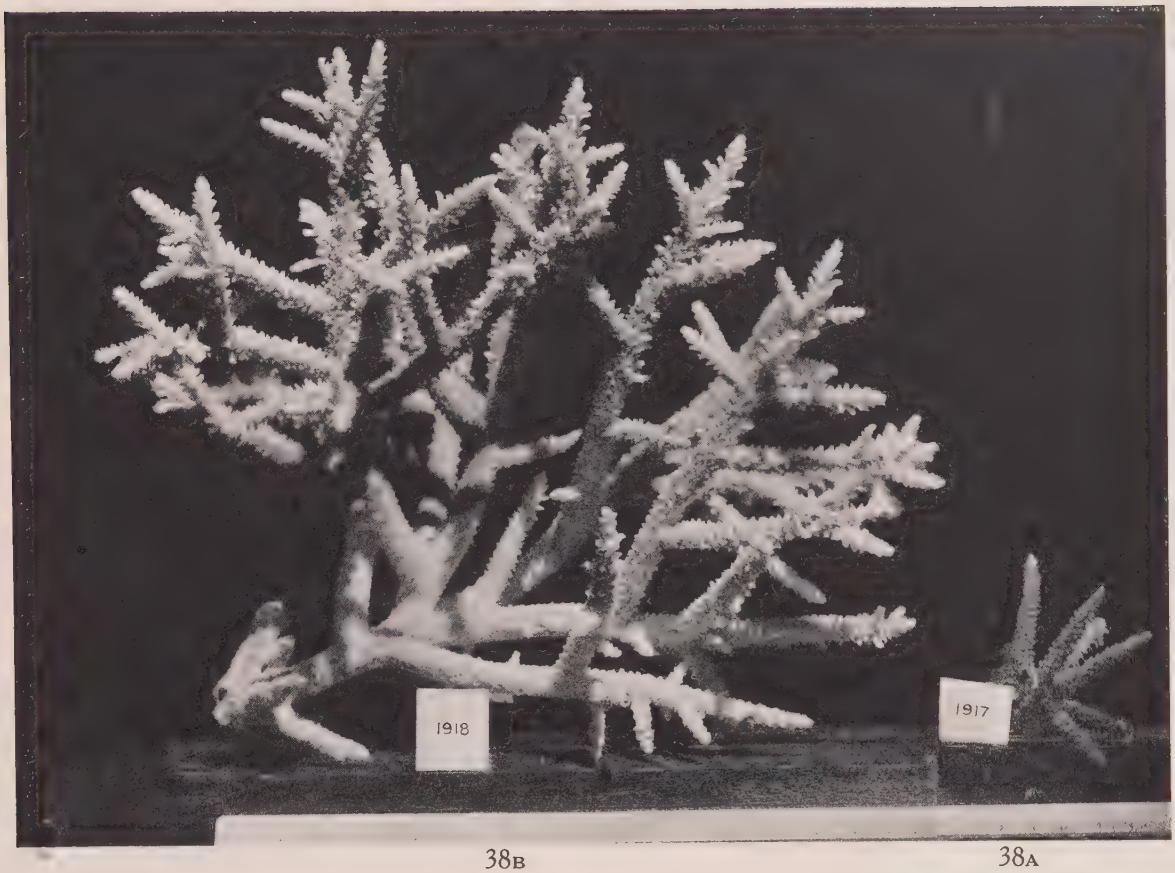
36B

Fig. 36.—Leptastrea purpurea (Dana).

37A

37B

Fig. 37.—Porites aff. P. lutea M. Edw. and H.



38B 38A

Fig. 38.—Acropora aff. formosa var. gracilis (Dana).

48A

48B

Fig. 48.—Galaxea fascicularis (Linn.).

49A

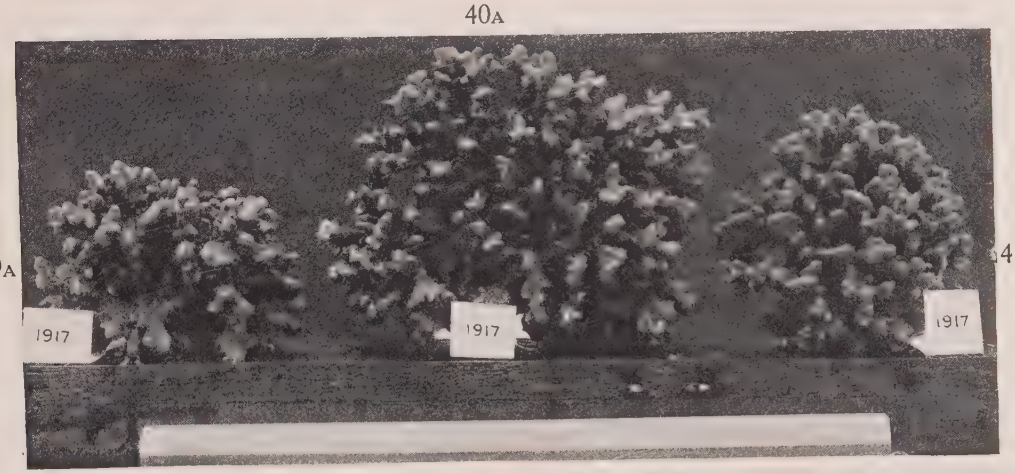
49B

Fig. 49.—Pavona frondifera Lamarck.

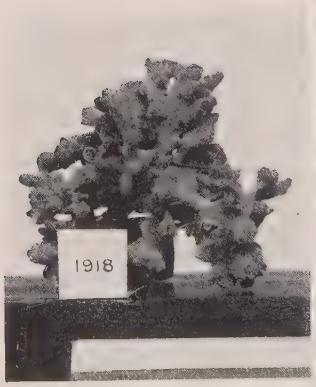
40A

39A

41A

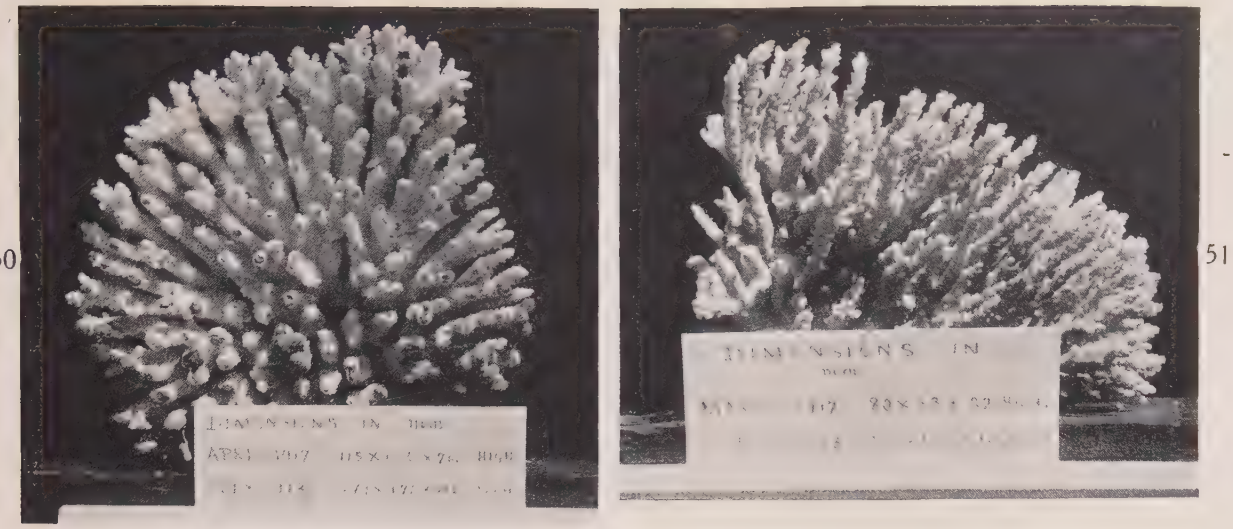


39B



40B 41B

Figs. 39 to 41.—Psammocora contigua var. maldivensis Gardiner.

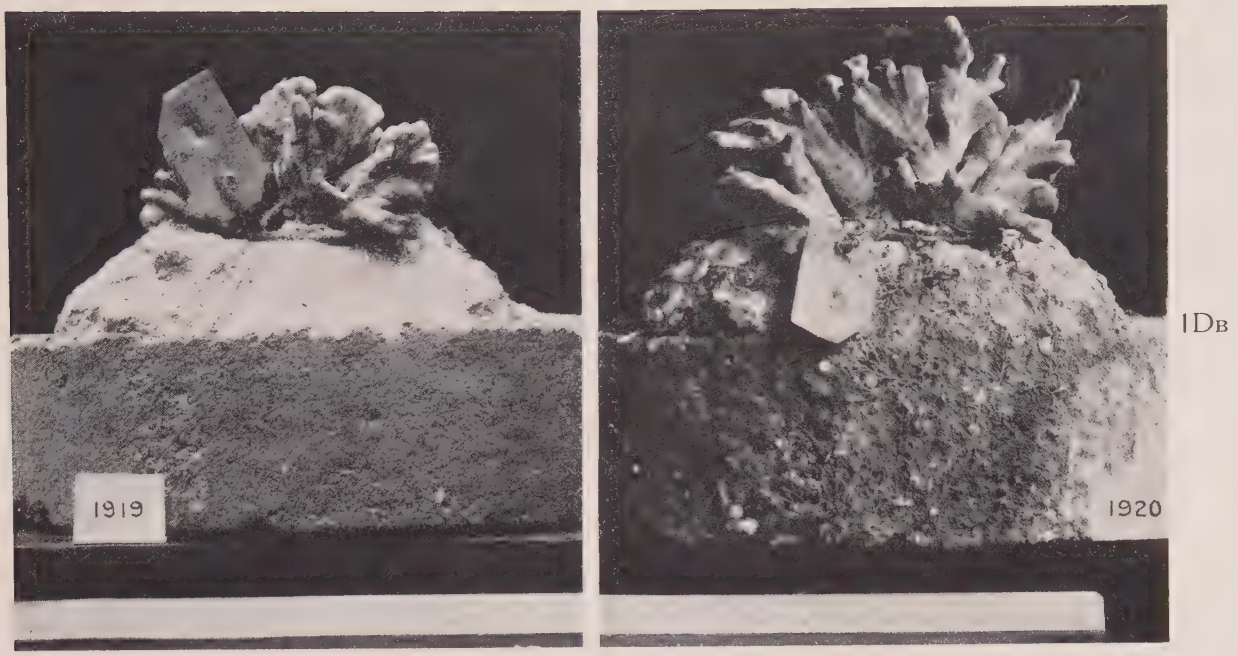


50 51

Fig. 50.—Acropora corymbosa (Lamarck).
Fig. 51.—Acropora syringodes (Brook).

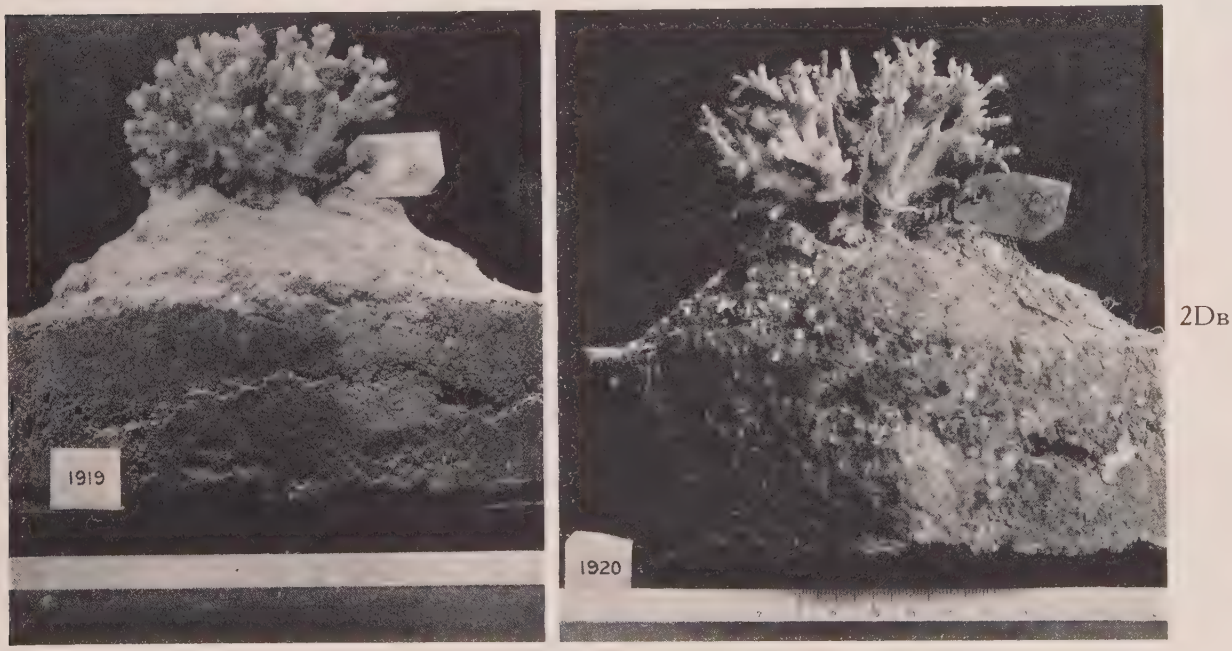
52

Fig. 52.—Porites lutea var. haddoni Vaughan.



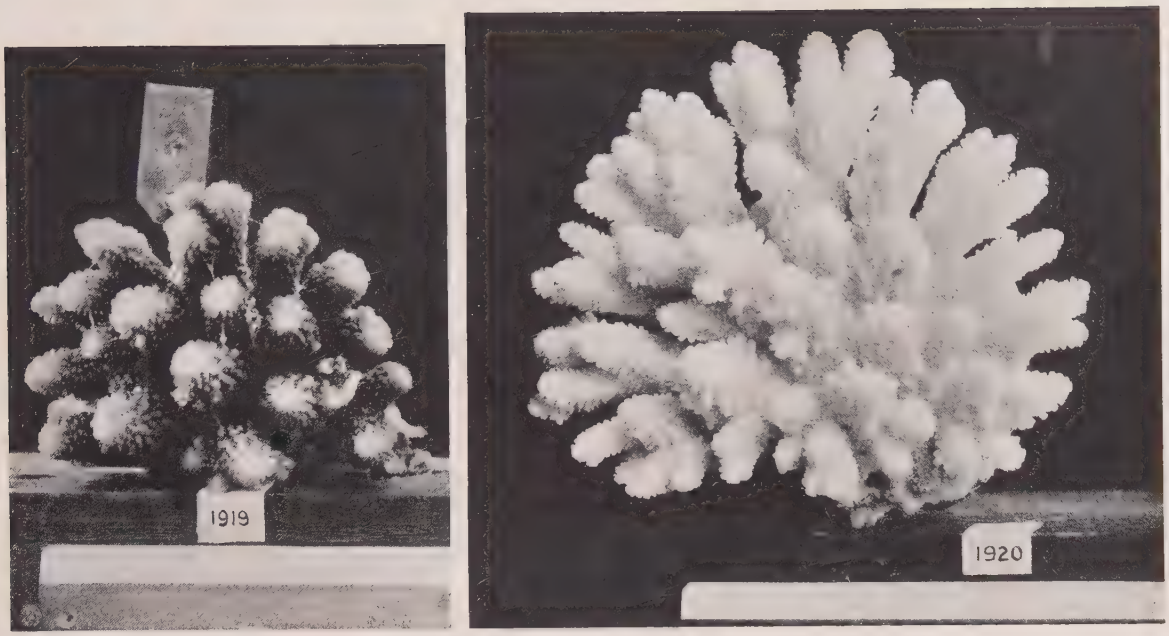
1DA 1DB

Fig. 1D. —Psammocora contigua Esper.

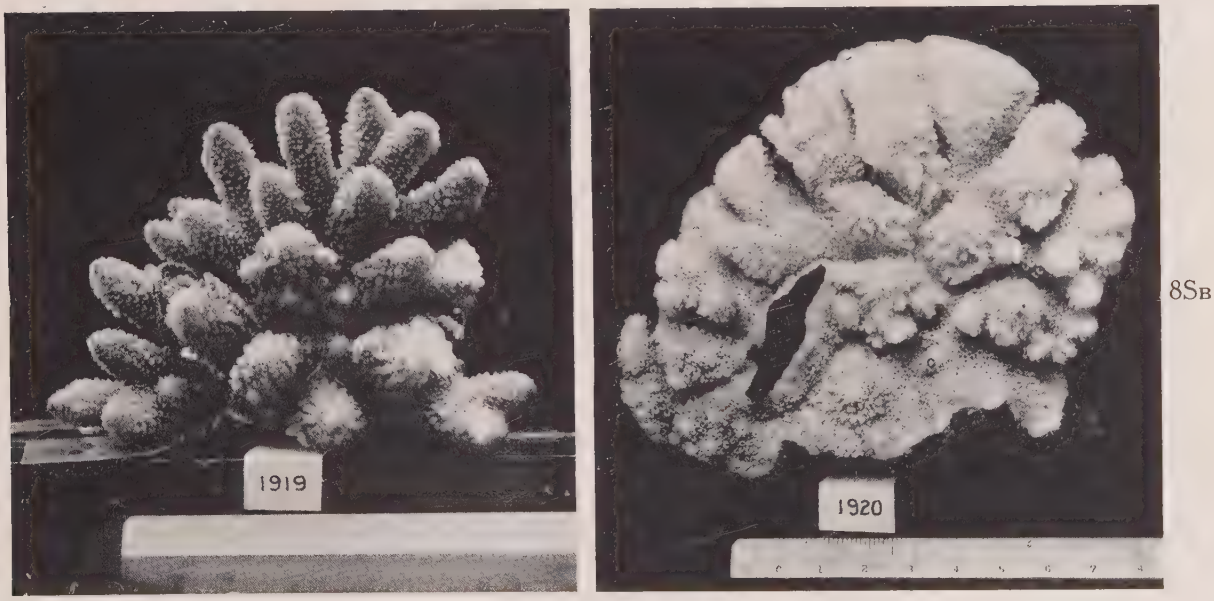


2DA 2DB

Fig. 2D.—Pocillopora damicornis var. cespitosa Dana.

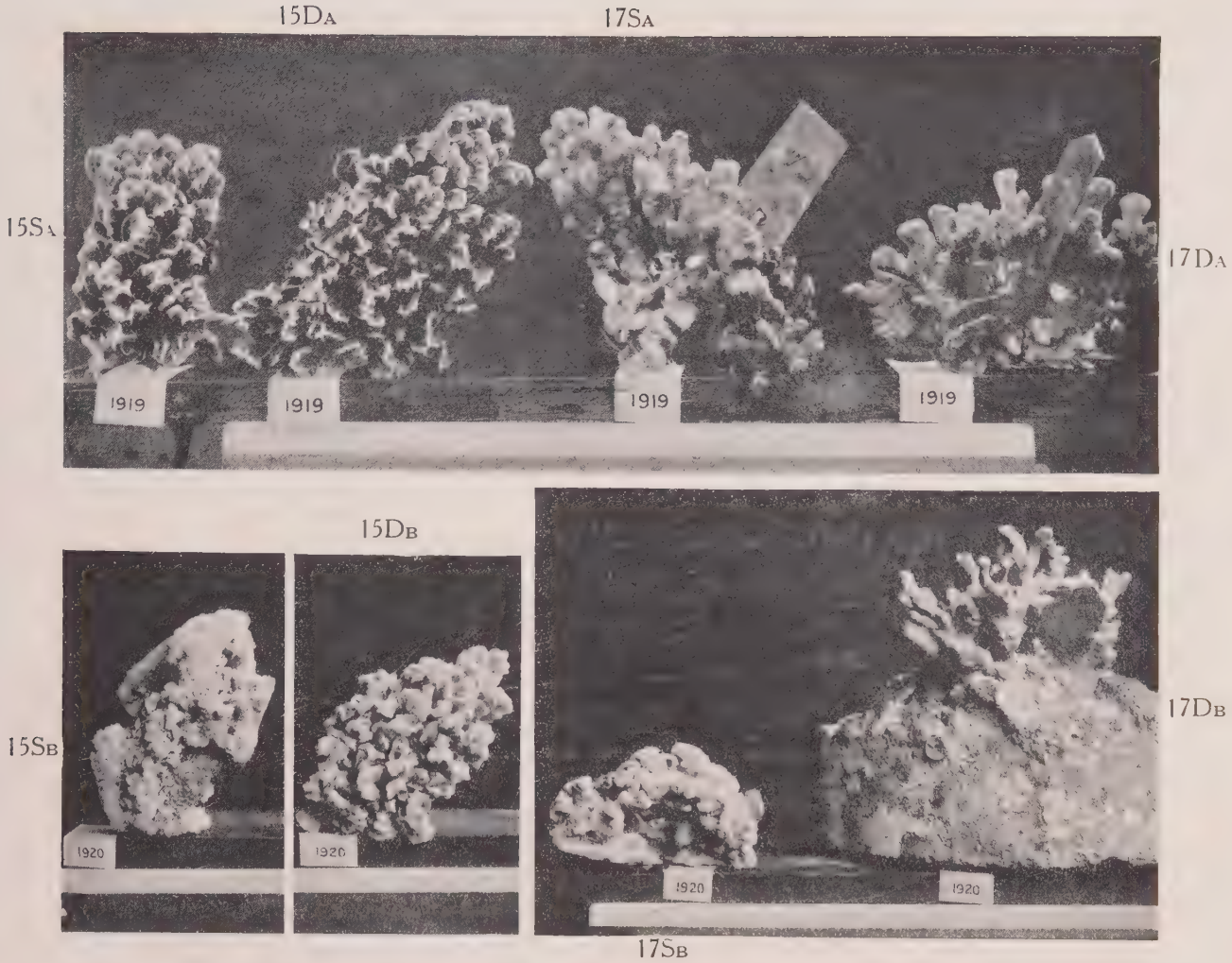


3SA Fig. 3S.—Acropora (Tylopora) leptocyathus (Brook). 3SB

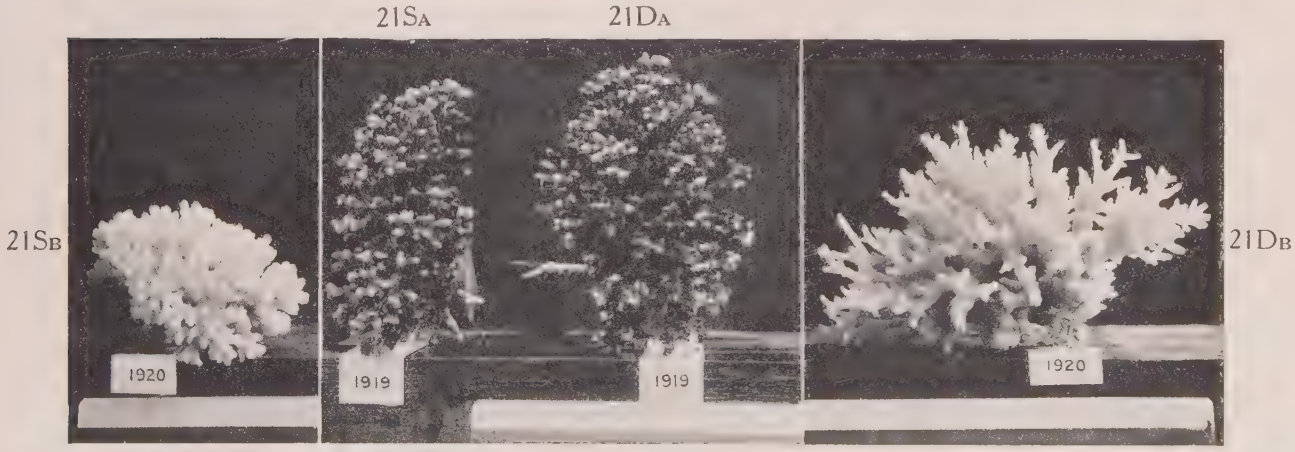


8SA 8SB

Fig. 8S.—Acropora (Tylopora) leptocyathus (Brook).

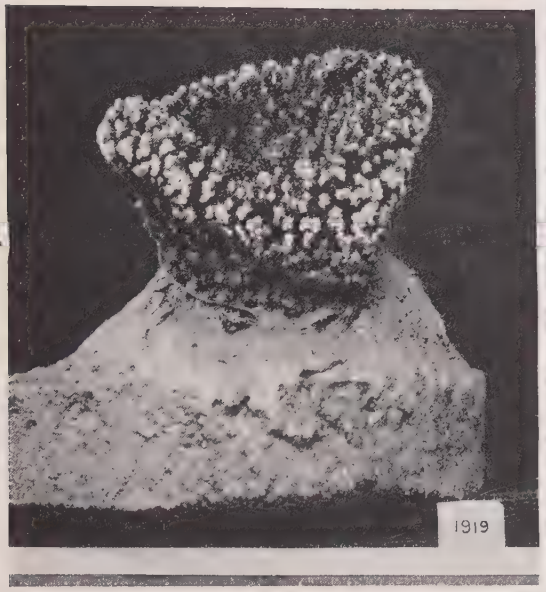


Figs. 15D, 15S.—Pavona divaricata Lamarck.
Figs. 17D, 17S.—Psammocora contigua var. maldivensis Gardiner.



Figs. 21S, 21D.—Pocillopora damicornis var. cæspitosa Dana.

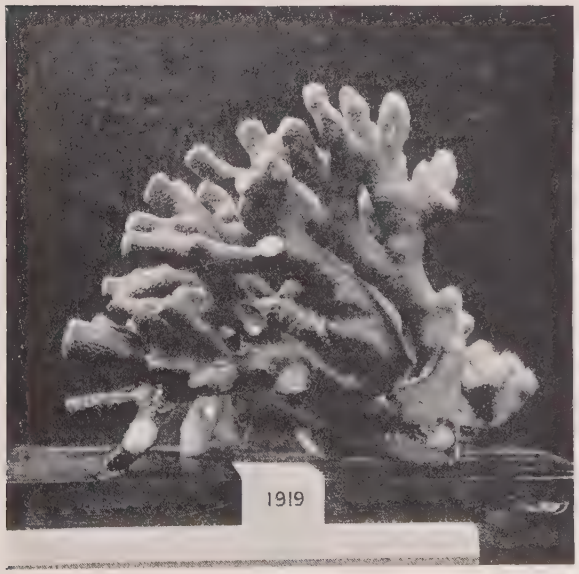
32DA



32DB

Fig. 32D.—Acropora hyacinthus (Dana).

24DA



24DB

Fig. 24D.—Porites andrewsi Vaughan.

33DA

33DB

Fig. 33D.—Pocillopora eydouxi M. Ed. and Haime.

35DA

35DB

Fig. 35D.—Acropora hyacinthus (Dana).

35DB

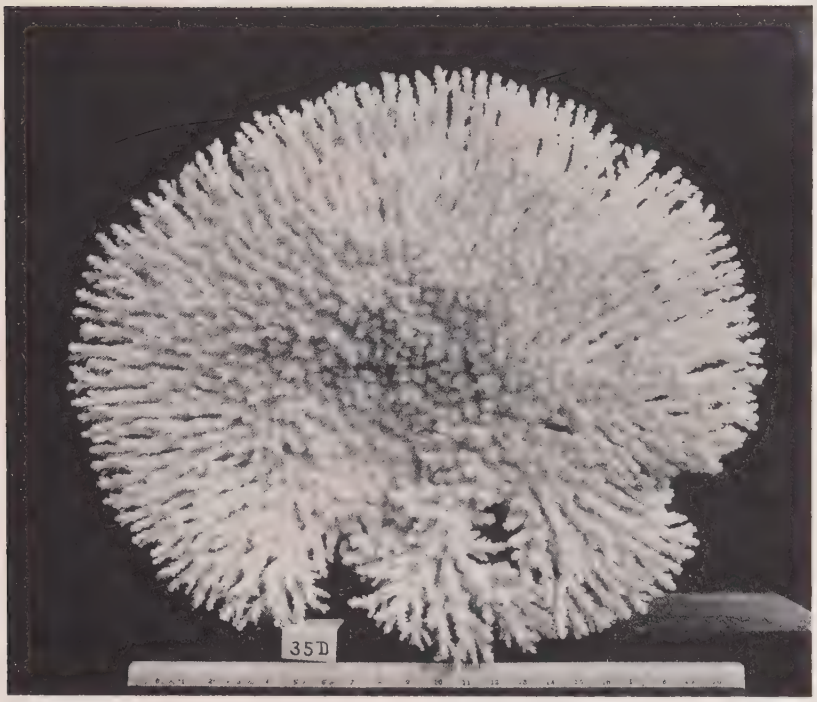
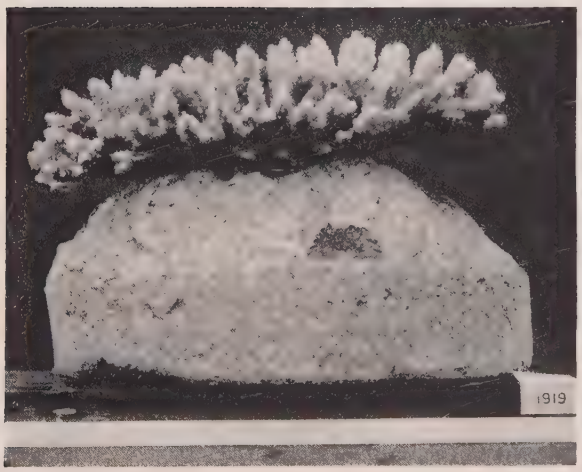


Fig. 35D.—Acropora hyacinthus (Dana). Top view.

36DA



36DB

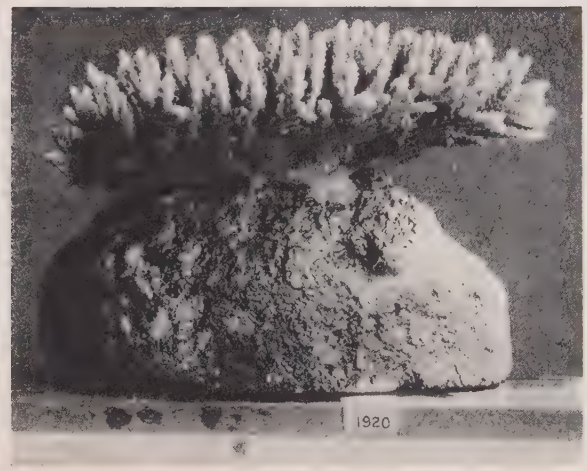


Fig. 36D.—Acropora cymbicyathus (Brook).

40D$_A$ 40D$_B$

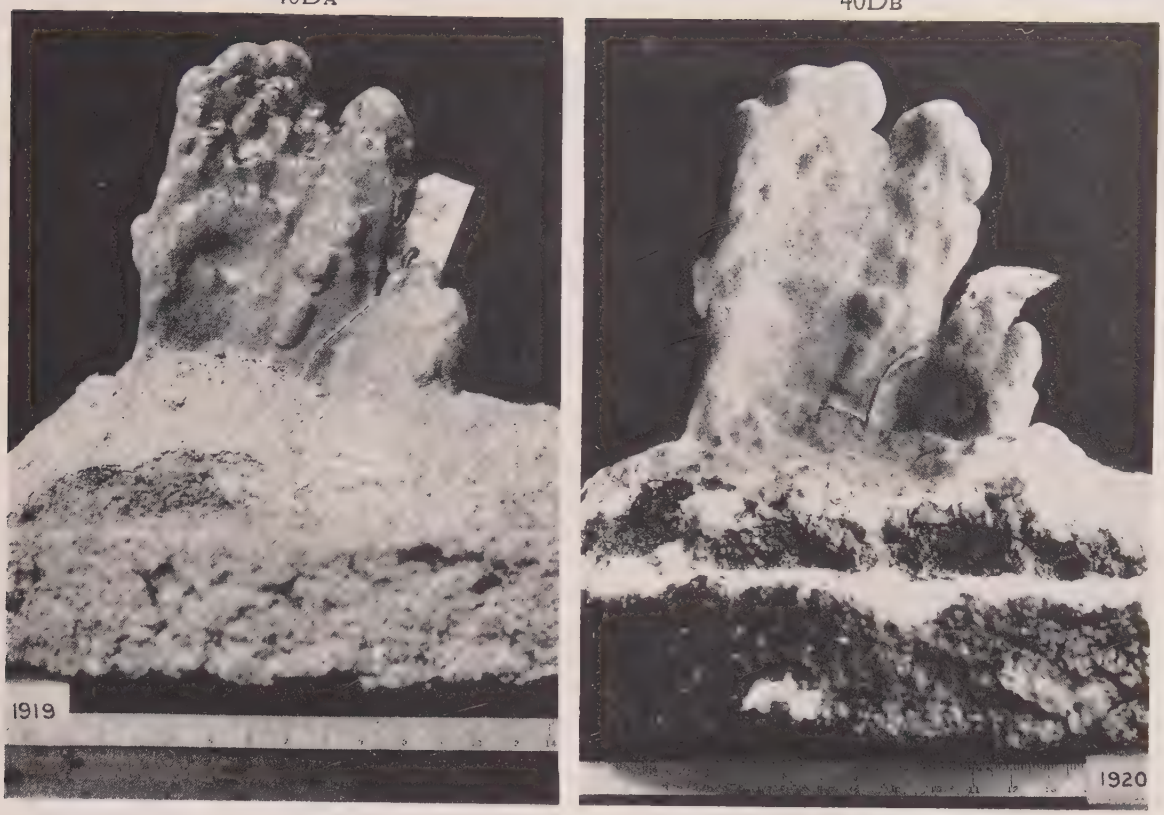


Fig. 40D.—Millepora truncata Dana.

41D$_A$ 41D$_B$

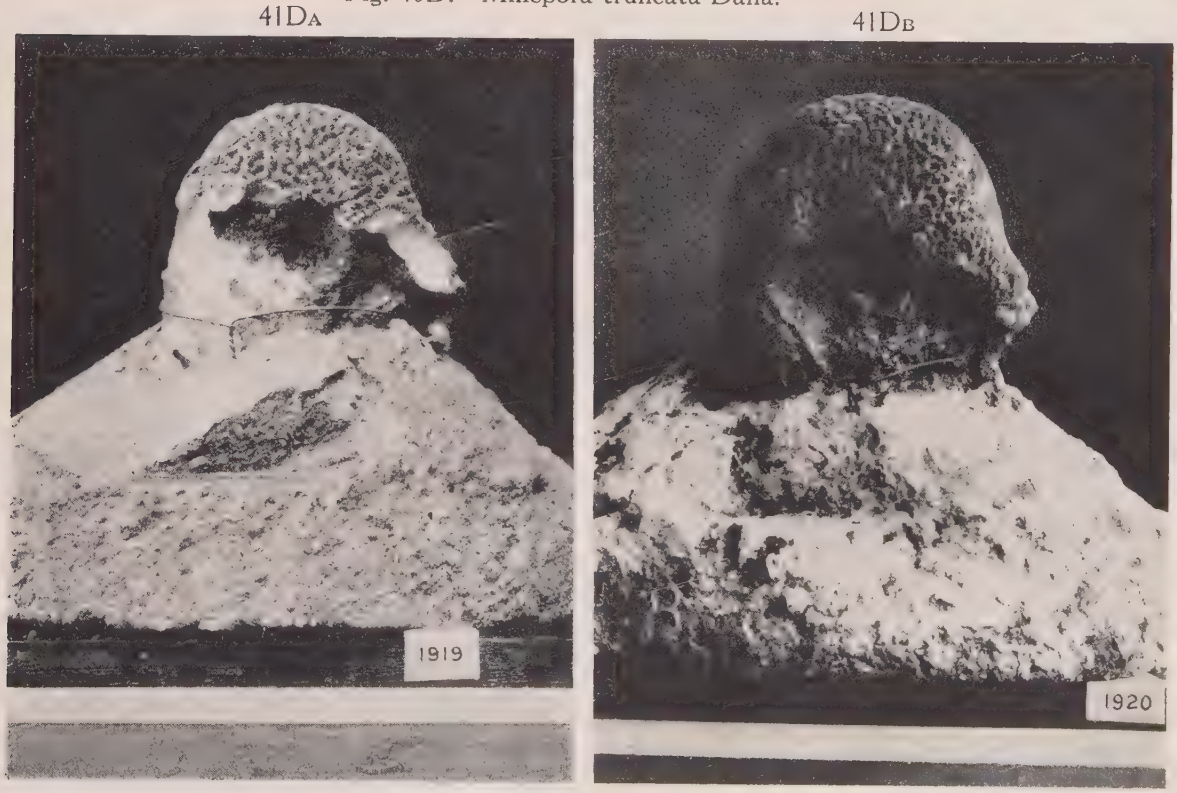
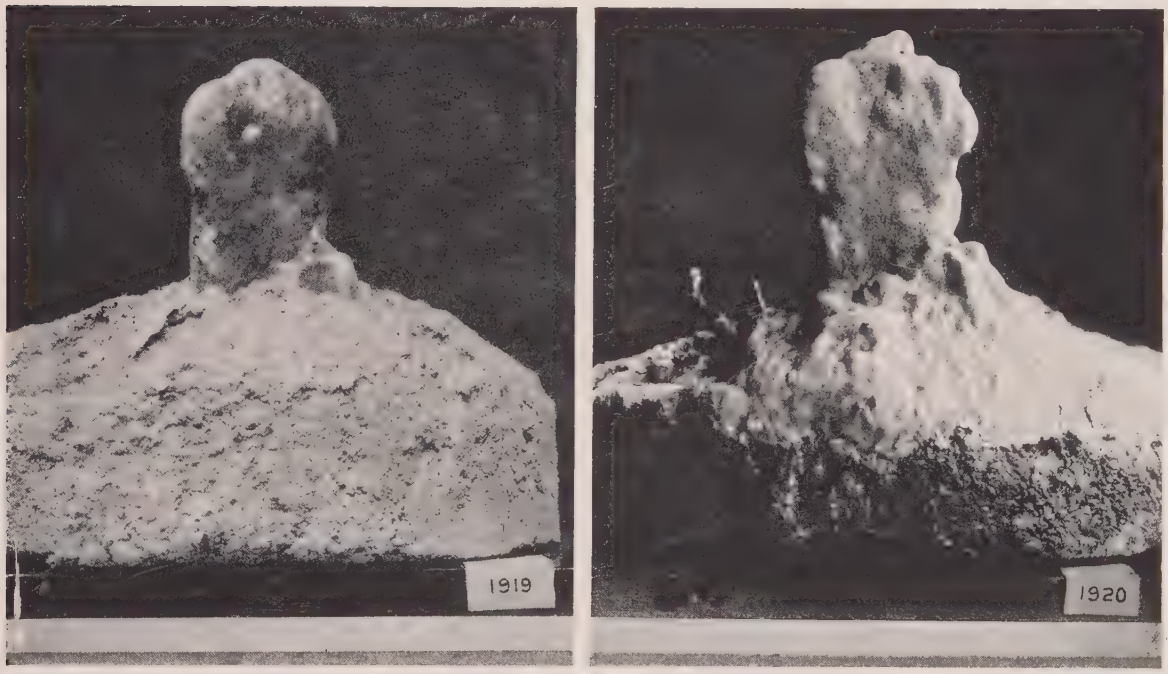


Fig. 41D. Coscinaræa columna (Dana).

42DA 42DB

Fig. 42D.—Pocillopora eydouxi M. Ed. and H.



44DA 44DB

Fig. 44D.—Millepora truncata Dana.

47D$_A$

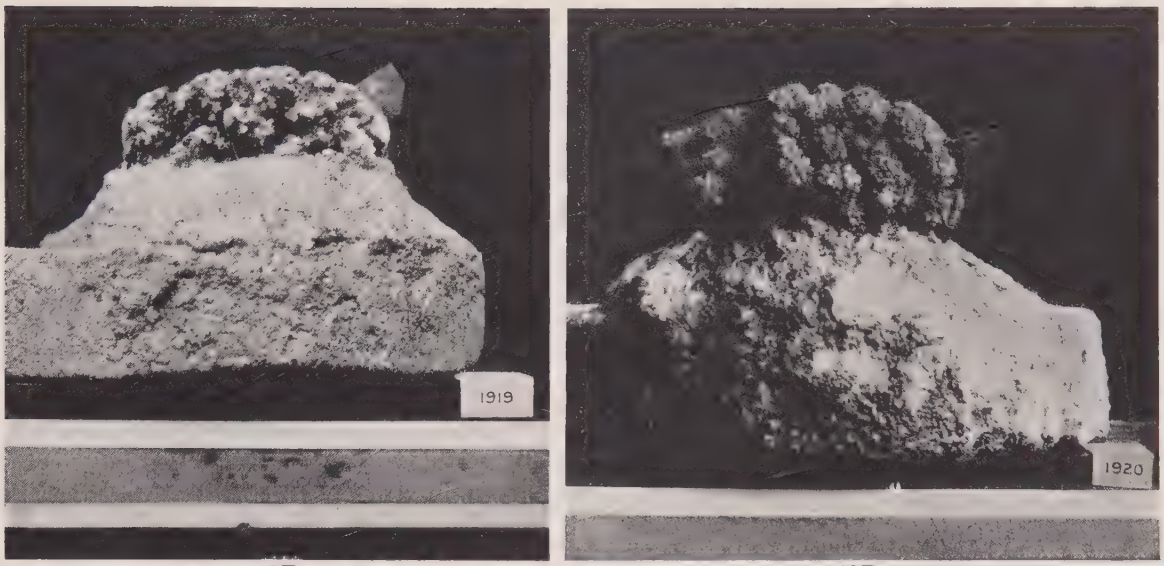
47D$_B$

Fig. 47D.—Acropora tutuilensis, Hoffmeister.

45D$_A$

45D$_B$

Fig. 45D.—Pocillopora damicornis var. cespitosa Dana.

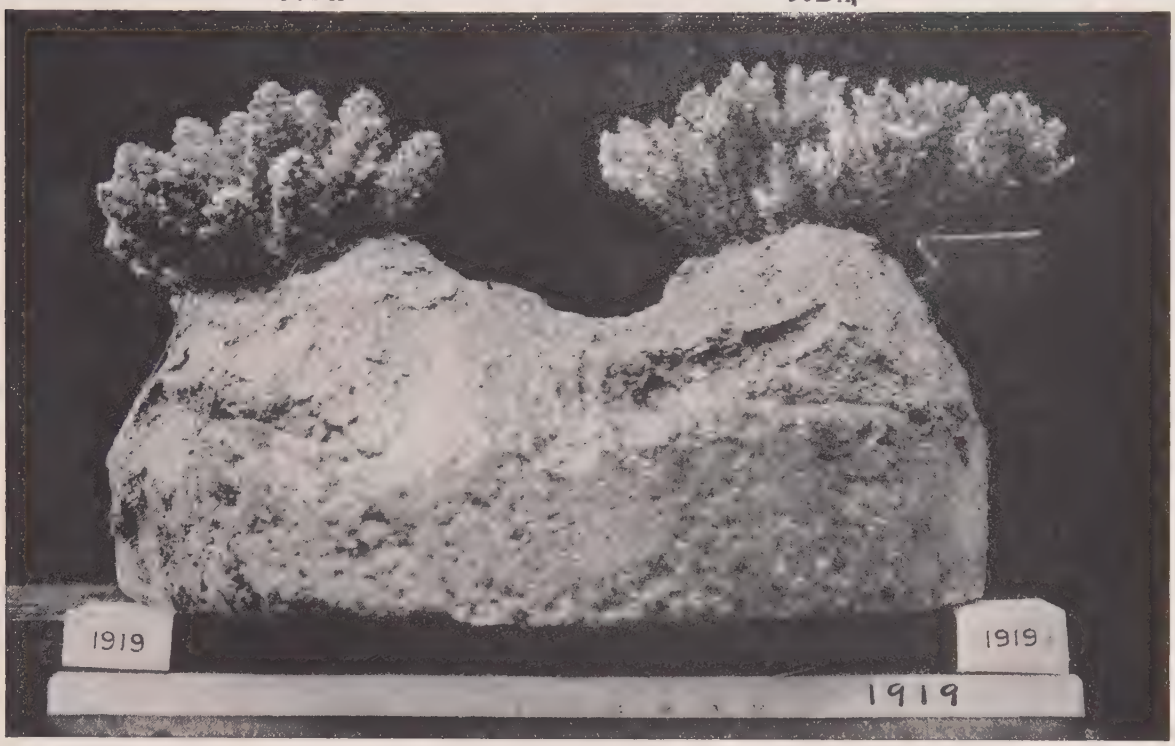


49DA 49DB

Fig. 49D.—Pocillopora brevicornis Lamarck.

Fig. 64F.—Fungia paumotensis Stutchberry.

51DA 50DA



51DB 50DB

Fig. 50D.—Acropora hyacinthus (Dana).
Fig. 51D.—Acropora valida (Dana).

ROSE ATOLL, AMERICAN SAMOA.

By Alfred Goldsborough Mayor.

The late Commander Warren Jay Terhune, U. S. N., then governor of Samoa, kindly invited me to accompany him on the U. S. S. *Fortune* to visit the little-known Rose Atoll in S. lat. 14° 32′, W. long. 168° 12′, and we spent 24 hours upon this island on June 5 and 6, 1920.

The island is an atoll, the lagoon being encircled by a narrow ring of limestone composed chiefly of lithothamnium, which is everywhere nearly awash at low tide, excepting on the northeast side, where there is a narrow entrance about 6 to 9 feet in depth, out of which a current constantly flows. The ring of limestone which surrounds the lagoon is quite uniformly about 500 yards in width, while the central lagoon is about 2 miles wide and appears to have a maximum depth of not more than 8 fathoms. There are only two small islets upon the atoll rim—Sand Islet and Rose Islet. The official map of the atoll[1] is the U. S. hydrographic chart of the Samoan Island, No. 90, based largely on the survey of the United States exploring expedition in 1839, and a map by Captain Rantzau (Journal des Museum Godeffroy, Hamburg, 1873, Heft 1, p. 32). This shows Rose Islet as occupying the entire width of the atoll rim, whereas at present it is confined to the inner half of the width of the reef-rim. Moreover, this chart shows trees covering the entire area of the islet, whereas at present only the southern half of the islet bears trees. The chart states that Rose Islet is 33 feet high, but at present the land of the islet is 11 feet above high tide and the tallest trees, as measured by means of a sextant, are about 80 feet high, and thus the total height of the landfall as seen from the ocean is about 90 feet. Indeed, the domelike cluster of *Pisonia grandis* trees presents so much the appearance of a hill (fig. 1) as seen from the ocean that a trading captain who had sailed past the island but never landed upon it described it to me as a mound of volcanic rock.

Rose Islet is at present about 240 yards SSW.–NNE., and about 200 yards wide. The southern and southeastern half of the islet is densely covered with a forest composed exclusively of *Pisonia grandis* trees, casting so complete a shade that no other plants grow beneath them (fig. 5), save only a single coconut palm which was probably planted by Governor Tilly's party about 15 years ago. This forest forms a nearly symmetrical dome, the leaves and branches on its confines extending quite to the ground (fig. 4). The largest trees are near the southern end of the grove. About 3 feet above the ground one of these trees had a girth of 25 feet 7 inches, and was about 80 feet high. The ground under these trees is covered with a rich chocolate-colored humus which is of considerable depth near the southern end of the grove.

[1] The first chart is that of L. C. D. Freycinet, made in 1819, at the time of the discovery of the island.

Apart from this grove of *Pisonia* trees and a half-dozen coconuts planted by Governors Tilly and Terhune in 1902 and 1920, there are only two other species of plants upon the islet. These have been identified by Professor William A. Setchell, and are a pink-flowered creeping *Boerhaavea diffusa* with stems rarely more than 3 feet long, and a thick-stemmed succulent *Portulaca* nov. sp. with small yellow flowers. Both of these plants grow fully exposed to the sun on the coral breccia and calcareous sand which surrounds the *Pisonia* grove, and none is found under the shade of the trees.

On the southeast side of Rose Islet the sand-beach is reduced to from 1 to 5 feet in width at low tide, and cliffs of coquina from 5 to 8 feet high front the sea (fig. 6). A few feet inland this rocky ledge rises to a height of about 11 feet above high-tide level. The *Pisonia* grove appears to be confined to this region of coquina rock and does not extend to any great extent over the loose calcareous breccia which has been washed in upon the islet in time of storm.

The tree-covered rocky center of the islet is composed of a coquina consisting chiefly of wave-worn fragments of lithothamnium and also rare and occasional fragments of broken coral, such as *Favites*, *Porites*, *Symphyllia*, *Pocillopora*, and still more rarely *Acropora*. Embedded in it are many wave-worn half-valves of *Tridacna* and gasteropod shells, and spines of *Echini* such as *Cidaris* were found, as was also the much corroded ulna and part of the skull of a small cetacean about the size of a blackfish, the latter being embedded in the coquina about 8 feet above high-tide level. A large amount of organic matter, dark brown in color and derived from the decomposed roots of the *Pisonia* trees, permeates this coquina to a depth of several feet. All of the fossils found embedded in the coquina are forms now living on the reef-flat, which have simply been tossed on shore by the waves. Professor C. B. Lipman found that this coquina in contact with the soil contains 12.05 per cent of phosphoric acid.

On the wave-washed southeastern shore of Rose Islet some modern beach-rock has been formed and projects a few inches above high-tide level; but this is more recent than the rocky matrix of the islet, which is now emerged about 11 feet above high-tide level.

Sand Islet, which lies north of Rose Islet, is a mere accumulation of fragments of lithothamnium, shells, and broken coral and is devoid of vegetation and only about 5 feet above high-tide level. The sea must wash completely over it in time of storm.

Several hundred boobies (*Sula*), most of which had half-grown young, were nesting on the coral breccia of Rose Islet (fig. 7), while others had constructed nests of sticks high among the branches of the *Pisonia* trees. A few boatswain-birds with eggs were also nesting in the trees, and several nearly grown young of the noddy (*Anous*) were running over the ground, while adult noddies and sooty terns visited the island at night. Frigate-birds were hovering over the island, but none were nesting. Wilkes states that the noddies and sooty terns were nesting on Rose Islet on October 7, 1839, and these species were still nesting when Governor Terhune visited the island on January 10, 1920.

A small brown-gray rat was abundant and specimens of it were presented to the Bishop Museum in Honolulu, where they were identified by Mr. J. F. G. Stokes as being a Malayan form which appears to have become widely spread over Polynesia, being possibly introduced by the early Polynesians themselves, who esteemed them for food, and took much delight in hunting them for sport. Apart from these very tame and abundant rats, the only other animals we observed were a small brown, short-tailed lizard, identified by Dr. Thomas Barbour as *Lepidodactylus lugubris* (Dumeril and Bibron), and which is widely distributed over Polynesia, and the larva of a sphinx moth of the genus *Celerio* (Oken) feeding upon the *Portulaca*. A few gnats and an occasional house fly which may have been introduced from the U. S. S. *Fortune* were the only other insects we observed.

The upper surface of the atoll-rim which encircles the lagoon is a hard, smooth-floored flat with but little loose sand upon it, and in most places it is awash at low tide, although in others it projects as a hard, smooth ledge about a foot above low tide of the neap tides.

This hard, smooth upper surface of the atoll-rim, veneered everywhere by a layer of lithothamnium, is characteristic of the wave-washed surface of offshore and barrier reefs of the Pacific. The condition over a fringing reef is quite different, for here loose fragments are washed inward from the seaward edge and backed up against the shore. Thus the whole surface, excepting only the wave-washed outer edge, is covered with small, loose fragments which could not remain upon an atoll-rim or a barrier reef, for they would soon be washed off into the lagoon. The relatively loose nature of the material forming the shoreward parts of fringing reefs at once distinguishes them from offshore reefs. Professor W. M. Davis's attempt, following Darwin, to institute a class of "offshore fringing reefs" is not justified, the structure of the two forms of reefs being widely different. As a matter of fact, reefs along Pacific shores are either barrier reefs or fringing reefs, and one is never in any doubt in distinguishing the one from the other.

Hundreds of large blocks of limestone lie scattered over the flat, wave-washed rim of Rose Atoll (fig. 2). These loose boulders are quite uniformly about 5.5 feet high, and only when tilted are they any higher (fig. 3). In addition to these boulders there are a few others which are mushroom-shaped and still remain attached to the floor of the atoll-rim, of which indeed they form an integral part. One of the most remarkable of these mushroom-rocks lies to the eastward of Rose Islet, and is supported upon so slender a pedicel that it would seem as if the next storm must cause it to topple over. In many places over the flat, wave-washed floor of the atoll-rim one finds remnants of pedicels which once supported "mushrooms." In addition, some of the boulders have become secondarily cemented to the floor of the flat by the growth of lithothamnium around their bases. The largest boulder we observed lay loosely upon the reef-flat east of Rose Islet and was somewhat tilted by being jammed against another rock. It was 12 feet 5 inches long, 8 feet wide, and 7 feet 6 inches high, and as its specific gravity was 2.3, it apparently weighs 46 tons.

The appearance of these boulders supports the view that the atoll-rim was once about 6 or 8 feet higher, in respect to sea-level, than at present, and has been cut down to present sea-level in recent times. The "negro heads" are simply mushroom rocks which have been completely undercut, so that they now lie loosely upon the floor of the flat.

It can be seen that the surface of the present reef-flat consists chiefly of lithothamnium, a beautiful bright pink variety of which (*Porolithon*) forms a veritable veneer almost to the exclusion of other forms of life. Professor Alexander H. Phillips made an analysis of this lithothamnium and found it to contain 74.4 per cent of calcium carbonate and 19.47 per cent magnesium carbonate. Also, rock from the solid floor of the atoll-rim west of the main entrance to the lagoon gave 83.86 per cent of calcium carbonate and 14.36 per cent of magnesium carbonate, while a large loose boulder from the same region consisted of 77.28 per cent of calcium carbonate and 18.3 per cent of magnesium carbonate. Professor C. B. Lipman found that the largest erratic boulder on the reef-flat east of Rose Islet contained 79.5 per cent calcium carbonate and 14.54 per cent magnesium carbonate. It will be recalled that Högbom found the magnesium carbonate in various species of *Lithothamnium* to range from 3.76 to 13.19 per cent. (See J. W. Judd, Funifuti Report, 1904, p. 377.) Also, in 1917, F. W. Clarke and W. C. Wheeler (U. S. Geological Survey, Professional Paper No. 102, p. 44) analyzed 16 species of calcareous algæ of the genera *Lithothamnium*, *Archæolithamnium*, *Lithophyllum*, *Amphiroa*, *Phymatolithon*, and *Goniolithon* and found the calcium carbonate to range from 73.63 to 88.11 per cent, while the magnesium carbonate ranged from 10.93 to 25.17 per cent. The same authors (*loc. cit.*, p. 11) found that in madreporarian reef-corals the calcium carbonate is more than 99 per cent and the magnesium carbonate less than 1 per cent; whereas in alcyonarian corals, exclusive of *Heliopora*, the magnesium carbonate ranges from 6.18 to 13.79 per cent, thus being comparable in amount with its proportion in lithothamnia.

It thus appears that the loose boulders lying upon the atoll-rim have the same general chemical composition as the living lithothamnium of the rim itself, and are remarkable in that they contain a large amount of magnesium. In fact, these boulders are only remnants of the old rim, which was once about 6 or 8 feet above sea-level, but has been almost entirely planed down to the level of the present surface of the ocean, leaving only an occasional mushroom-rock or a pedicel as a vestigial remnant of the old rim.

Inspection shows that the solid rock of the atoll-rim and also the boulders lying upon it consist chiefly of *Lithothamnium* compacted into a mass of chalky whiteness superficially resembling dolomite and having a specific gravity of about 2.3, thus being higher than that of a pure coral limestone, the specific gravity of which would range from 1.85 to 2. A pure dolomite containing 45.65 per cent of magnesium carbonate should have a specific gravity of about 2.9.

There are a few fossil corals, chiefly *Pocillopora*, embedded in the rock of the atoll-rim and the boulders, but the whole visible rock of the atoll consists so largely

of *Lithothamnium* that we may call it a "*Lithothamnium* atoll" rather than a "coral atoll."

The flat upper surface of the atoll-rim is in most places planed off nearly to low-tide level, but it is veneered with a vigorous growth of a beautiful pink *Lithothamnium* which has been determined by Professor W. A. Setchell as *Porolithon* sp. closely allied to *P. craspedium*. In most places this *Lithothamnium* forms irregular, more or less connected patches growing on the smooth, hard floor of the flat. West of the main entrance to the lagoon, however, it grows in long, nearly parallel, flat-topped, overarching ridges, all parallel with the line of the wave-fronts of the breakers as they surge over the reef (fig. 3). These ridges are about 6 inches high and from 6 inches to several feet in width and with channels of similar width between them.

Lithothamnium grows in greater profusion over the reef-rim of Rose Atoll than in any other Pacific reef I have seen, but apart from the single species of pink *Lithothamnium* there are remarkably few organisms growing in the shallows of the reef-flat. Occasionally we find a pale olive-green *Porites*, allied to *P. lutea* M. Ed. and H., and there are a few small stocks of *Favites* or *Symphyllia;* but *Acropora* and *Pocillopora*, which are the dominant forms in most breaker-washed reef-flats of the Pacific, are practically absent from Rose Atoll, except at the extreme edges of the atoll-rim fronting the lagoon or the sea, where a few stunted specimens of these genera occur.

I did not find upon the Rose Atoll reef-rim a single specimen of branched *Acropora* related to *A. muricata*, nor did I see *Acropora hyacinthus*, or *A. leptocyathus*, which are dominant forms on the seaward edges of reefs elsewhere in Samoa.

Holothuria were fairly common, as were also small specimens of the giant clam *Tridacna*, and among echini a few *Cidaris* and black, long-spined *Diadema* were seen; and the bright-green seaweed *Caulerpa* was here and there found in the troughs between the ridges of *Lithothamnium;* yet apart from the single species of pink *Lithothamnium*, all other organisms were a negligible factor on the upper surface of the atoll-rim.

It is important to observe that among the hundreds of loose boulders scattered over the flat upper surface of the atoll-rim there are a few which still retain their connection with the floor of the flat and project above it as "mushroom" rocks, thus indicating either that the atoll-rim has risen 6 to 8 feet or that sea-level has sunken to this extent. The evidence, however, tends to sustain the view that sea-level has become lowered and not that the atoll-rim has risen, for there is no visible tilting of the rim; and moreover, all the volcanic islands of American Samoa are surrounded by a bench of volcanic rock which is uniformly about 10 feet above present high-tide level and is backed by sea-cliffs, thus suggesting that these islands have remained stationary while sea-level has become lowered.

In this connection it may be of interest to observe that with the exception of Mangareva, which is volcanic, and Makatea, which is elevated coral limestone, all of the atolls of the Paumotus exhibit a bench of old limestone now several feet above present high-tide level. It will also be recalled that David and Sweet, in their

account of the geology of Funafuti (Funafuti Report, 1904, p. 84), conclude that in this atoll there must have been either a land-elevation or a sea-sinking of at least 9 to 10 feet. In 1913 we observed a sea-bench of about 3 feet above highest tides around the volcanic, calcareous, and continental islands of Torres Straits, and, according to W. J. Dakin (1919, Journ. Linnean Soc. London, vol. 34, p. 127) an 8-foot bench is found throughout the Houtman Islands off the west coast of Australia.

As there are fossil corals and *Lithothamnium* in the highest parts of the boulders and mushroom-rocks on the rim of Rose Atoll, it appears that the climate was tropical when the sea cut the now emerged 8-foot bench around all the volcanic islands of American Samoa.

In the Funafuti boring the percentage of magnesium in the core ranged from 4 per cent at a depth of 4 feet to 16 per cent at 15 and 26 feet, below which it declined to 3 per cent at a depth of 60 feet. Judd attributes this high percentage of magnesium to the supposed leaching-out of calcium by the sea-water, but we now know that the surface waters of the tropical Pacific are supersaturated in respect to calcium carbonate and that calcium carbonate is therefore practically insoluble in this surface water. Judd admits that there is much *Lithothamnium* in this upper part of the boring, but unfortunately he made no analysis of the magnesium contents of any lithothamnia at present growing upon the Funafuti Reef; and judging from the conditions at Rose Atoll, I am inclined to believe that the magnesium in this upper part of the Funafuti boring is due solely to its being largely composed of *Lithothamnium* and not to any leaching-out of calcium carbonate. This conclusion is supported also by the fact that in the Funafuti boring between 100 feet and 637 feet in depth the magnesium carbonate was nowhere greater than 5.4 per cent; yet, if calcium leached out in water about 26 feet deep, why did it not leach out at these greater depths, where conditions of temperature and hence of carbon dioxide are more favorable for solution?

J. P. Couthouy (1844, Boston Journal of Natural History, vol. 4, p. 138) says of Rose Atoll:

> A number of boulders of volcanic rock are scattered over the sandy bottom of the lagoon, one of about 20 pounds being found in about 4 feet of water. This rock was similar in appearance and mineral structure to that constituting the neighboring groups of Samoa and Fiji.

Also, Wilkes (1852, Narrative of the U. S. Exploring Expedition, vol. 1, p. 155) states: "Some boulders of vesicular lava were seen on the coral reef of Rose Atoll; they were from 20 to 200 pounds in weight and were found among blocks of coral conglomerate." After diligent search I was unable to find any volcanic rock upon Rose Atoll, and it seems probable that Couthouy and Wilkes mistook some dark-colored scoriaceous-looking, weather-worn limestone boulders for lava.

A.—Rose Atoll from about a mile off northwest entrance to the lagoon, showing hill-like contour of grove of Pisonia trees.

B.—Boulders on reef-flat east of Rose Islet.

C.—Boulder on reef-flat west of main entrance to lagoon, showing rows of Archæolithothamnium growing in shallow water of reef flat.

A.—Coquina ledge on southeast side of Rose Islet.
B.—Booby with two young, one much older than the other, resting on the breccia near edge of the Pisonia grove of Rose Islet.

SUMMARY.

The visible part of the rim of Rose Atoll is composed of *Lithothamnium* rather than of coral, and is chiefly constituted of the same pink-colored species of *Lithothamnium* (*Porolithon*) now found growing over the shallows of the reef-flat.

The atoll-rim was once at least 8 feet higher than the present sea-level, and has been largely planed down to present sea-level by the (possibly lowered) ocean of modern times.

In common with Rose Atoll, all the volcanic islands of American Samoa indicate that sea-level was at least 8 feet higher than at present.

The rock of the atoll-rim contains from about 14 to 19 per cent of magnesium carbonate, due to its being composed largely of *Lithothamnium*, but not due to any appreciable dolomitization of the limestone after its formation.

As fossil corals and *Lithothamnium* are found in the highest parts of the remnants of the old Atoll-rim, it appears that the climate of American Samoa was tropical at the time when the sea may have stood at least 10 feet higher than at present.

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THE GEOLOGY OF AMERICAN SAMOA.

By

Reginald A. Daly, *Harvard University.*

With eleven plates and one text-figure.

THE GEOLOGY OF AMERICAN SAMOA.

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GEOGRAPHICAL RELATIONS.

The Samoan Islands lie between 168° and 173° west longitude and between 14° 35′ and 13° 20′ south latitude (fig. 1). The group is a chain, 520 km. long, trending south 75° east from the western end of Savaii. Named in order from west to east, the principal islands are:

	Distance from shore to shore.	Approximate area.		Maximum height.	
British Samoa:	*km.*	*sq. miles*	*sq. km.*	*feet*	*meters*
Savaii	....	700	1,800	6,094	1,858
Apolima	6	2	5	472	144
Manono	2	3	8	197	60
Upolu	2	430	1,100	ca. 3,900	ca. 1,189
American Samoa:					
Tutuila (with Aunuu)	67	54	138	2,141	653
Ofu (with Nuu)	95	2	5	1,590	485
Olosega	0.1	1.5	4	2,095	638
Tau	7.5	15	39	3,056	931
Rose	140	0.3	0.8	ca. 10	ca. 3

With the exception of Rose Island, an atoll, all the islands are inhabited. In 1917, before the disastrous epidemic of influenza in 1918, all western Samoa (British Samoa) had a population of about 37,000 natives, 1,500 Chinese coolies, and 1,600 whites. American Samoa, quite untouched by the epidemic, has a native population of about 8,000 persons, of whom about 5,000 dwell in Tutuila. Apia, in Upolu, the chief commercial port and the burial-place of Robert Louis Stevenson, is well known to the outside world. The volcanic eruptions of Savaii (Mauga Afi and Matavanu), during the first decade of this century, have made the largest island celebrated in geological circles.

The Samoan group lies nearly on the prolongation of the axis of the double volcanic chain which includes the Tubuai and Cook islands. This chain is about 2,500 km. long and is thus comparable with the Hawaiian chain. The Tubuai-Cook, Society, Paumotu, and Hawaiian chains are examples of volcanic upbuilding under the conditions reigning in the earth's crust far from any continent. The much shorter Samoan chain has much the same trend and rock-composition as those characterizing the Society and Hawaiian chains, but lies close to the submerged border of the Australasiatic continent. Figure 1 shows the relation of Samoa to the remarkable Tonga Deep, which runs about north 20° east from the northern extremity of the similar Kermadec Deep (K. D.). The general sea-bottom to

the eastward is at depths ranging from 4,000 to 5,000 meters. The maximum measured depth of the Tonga Deep is 9,184 meters; that of the Kermadec Deep is 9,427 meters. Their combined length is nearly 2,500 km. West of these narrow troughs are the submerged geanticlines bearing the Tonga and Kermadec Islands. A relatively shallow area, 350 km. wide, separates the Tonga group of islands from the Lau or Eastern Plateau of the Fiji group.

FIG. 1.—Relation of Samoa to the Tonga Deep and to Figi. Numbers show depths in thousands of meters.

Granite has been found in both the Fiji and Kermadec groups. These discoveries, coupled with the facts of general structure in Fiji, suggest that the true edge of the continental block of Australasia is situated along the line of the Tonga and Kermadec deeps, which are thus to be considered as possible homologues of the foredeeps facing the mountain arcs from the Philippines to Alaska. The overdeepening of the southern troughs is probably connected with tangential stresses

developed by the seaward thrust of the continental crust-block, of which Australia and New Zealand and their island satellites are the emerged parts. In any case the similarity of these troughs to the foredeeps farther north leads to the inference that the formation of the southern troughs was genetically associated with the continental border. If the local subsidence responsible for the Tonga Deep was continued into modern times, the Samoan ridge may be presumed to have been carried down with it. Local sinking of this kind is obviously not to be expected in the Pacific archipelagoes, far from any continent.

The stressed condition of the earth's crust, in and around the Tonga Deep, is shown by the high seismicity of the region. The older stone buildings of Samoa, such as the church at Asili and the Missionary Society headquarters at Leone, are badly cracked by earthquake shocks. For many years the seismographs of the Apia Observatory have recorded such vibrations. As yet we lack evidence as to whether the crustal slips represent further deepening of the Tonga trough or represent readjustments of the crust in consequence of deformation completed during the Tertiary orogenic revolution.

PREVIOUS WORK ON THE GEOLOGY AND GEOGRAPHY OF AMERICAN SAMOA.

In the *Abhandlungen der bayerischen Akademie der Wissenschaften* (math. phys. Classe, Band 24, 1907, pp. 509–541), I. Friedlaender has given the best general account of Samoan geology yet published. The petrography of his collections is described by M. Weber on pages 289–310 of the same volume. Friedlaender appended a bibliography, practically complete for the date of writing. Later publications, by A. G. Mayor, R. T. Chamberlin, and the writer, appear in the Year Books and special publications of the Carnegie Institution of Washington.[1]

The United States Navy Department has prepared excellent contour-maps of Tutuila and the Manua subgroup on the scale of 1 : 40,000. All of these appear on Chart No. 2924, issued by the Hydrographic Office at Washington. The accompanying Plate A, a reduced copy of the chart, also shows the many soundings made around Tutuila out to the depth of 100 fathoms. Owing to the kindness of Dr. G. W. Littlehales, hydrographer of the department, the writer was able to use these valuable maps in manuscript form. The geological map of Tutuila (Plate B) is based on one of these manuscripts.

During his stay in Samoa, Friedlaender made a special search for continental rocks such as granite, gneiss, schists, and quartzite. Apart from ship's ballast and imported stone implements, he found none. The experience of the present writer and of his colleagues has been the same. Except for thin veneers and intercalations of limestone, the island group seems to be wholly volcanic. Friedlaender notes the possibility that the volcanoes of the Hawaiian and Samoan chains may rest on geanticlines, analogous to that which is known to form the foundation of the Fijian volcanoes. There is no direct evidence favoring this hypothesis; it seems as likely

[1] See also *The Geology of Western Samoa*, by J. A. Thomson, New Zealand Journal of Science and Technology, vol. 4, 1921, pp. 49–66.

that the Samoan ridge is entirely due to volcanic extravasation. The relation of the Samoan chain to the Tonga Deep, above suggested, is not opposed to the second explanation of the great ridge.

Friedlaender described analogies between the Hawaiian and Samoan chains. At the eastern extremity of the northern chain is its largest island, Hawaii, with two vents active in recent years; at the opposite end is an atoll. At the western extremity of the Samoan chain is its largest island, Savaii (the name being the Samoan equivalent of the word "Hawaii"), with two vents which were active since 1900; at the opposite end of the chain is Rose Island, an atoll. The progress of erosion in the different Hawaiian islands shows a rather systematic increase of age for the island surfaces, in order from east to west. Here the analogy is more remote, for the lavas of Tau appear almost as fresh and undamaged by erosion as the staple lavas of Savaii. Between Tau and Olosega islands is the site of a submarine eruption, in 1866, again showing that the eastern half of the Samoan chain has witnessed volcanic discharge more recently than that registered at even the youngest vents of Tutuila, in the middle part of the chain. Tutuila is the most deeply eroded of all these islands, unless Rose atoll represents the case of the complete planation of a volcano formerly standing well above sea-level. Eastern Upolu is in part dissected, but on the whole the erosional relief of Upolu is at a stage intermediate between the erosional reliefs of Tutuila and Savaii.

Friedlaender (p. 533) sketched the geology of the different islands, and emphasized his observations on the eruption that took place at Matavanu, Savaii, at the time of his visit. In regard to the three largest islands he stated:

> The east-west directions of the mountain summits and the north-south directions of the igneous dikes are clearly apparent in each case. All three islands agree in showing that a principal crater is not present, that the western part of each island is the younger, and that at the eastern extremity of each island, a tuff crater, younger than the principal island and apparently of submarine origin, has been developed.

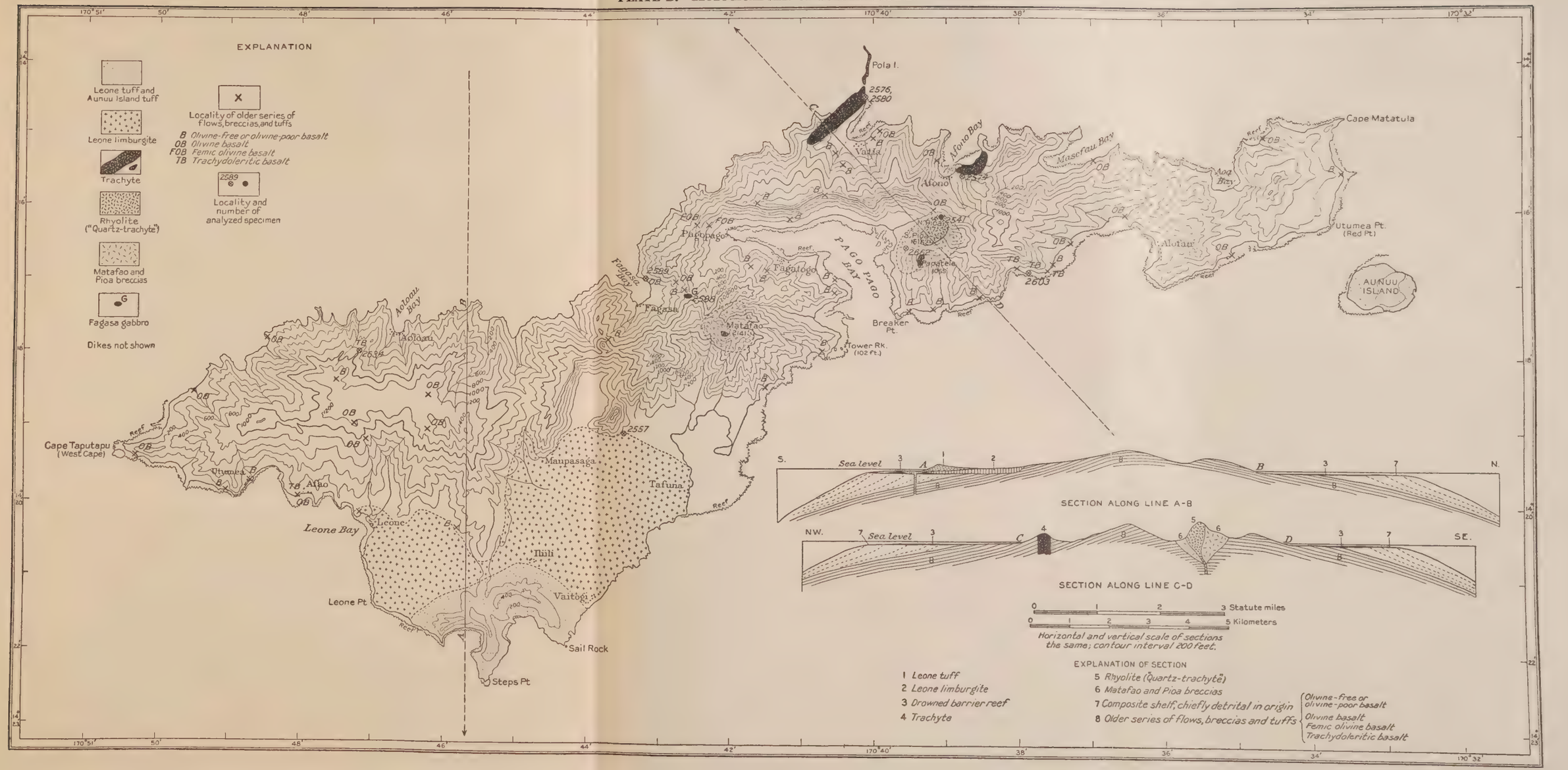
GEOLOGY OF TUTUILA AND AUNUU ISLANDS.

CONDITIONS OF FIELD WORK.

The strongly dissected surface of Tutuila is covered with a dense tropical jungle, except along the shores and in the comparatively small inland areas devoted to cocoanut, taro, and breadfruit plantations. (Plate 1.) Were it not for the numerous native trails, exploration of the interior would mean slow and tedious work. Most of the surface rock is deeply lateritized, good outcrops usually appearing only in stream courses or along the steep cliffs. Structural and petrographical studies are made much more satisfactorily along the shore, where outcrops of strong rock are nearly continuous; here, too, the trails are the best in the island. Thus, in spite of the jungle, 8 weeks sufficed for a fairly good reconnaissance of Tutuila.

It may be added, for the benefit of future explorers, that shelter and native food can be secured in almost every bay, the extraordinarily hospitable natives having occupied the shore wherever there is the least semblance of a harbor for their little fleets of outrigger canoes. White man's supplies can be had at Pago Pago and at Leone, the two best centers for field work.

PLATE B.—GEOLOGICAL MAP OF TUTUILA ISLAND.



ACKNOWLEDGMENTS.

The writer was greatly aided in the field work by the director of the expedition, the late Alfred G. Mayor, who freely shared his wide knowledge of the tropics and gave many concretes uggestions regarding geological problems and their solution. Hearty thanks are due to the Carnegie Institution of Washington for the privilege of spending a season at work in a most instructive and delightful region; and to Dr. Henry S. Washington, of the Geophysical Laboratory, who generously offered to contribute the ten rock-analyses, the statement of which forms a valuable part of this paper, and who calculated their norms.

CONSTITUENT FORMATIONS.

Tutuila is highly composite. A half dozen magmatic types are represented in the visible rock-bodies. Lava flows, composed of olivine basalt, limburgitic basalt, olivine-free and olivine-poor basalt, trachydoleritic basalt, and probably andesitic varieties, are interbedded with breccias and tuffs of basaltic or closely similar constitution. Many basaltic dikes, diabasic dikes, and rarer trachyandesitic dikes, as well as a neck of medium-grained, mafic gabbro, cut the dominant basaltic flows and pyroclastics. Highly alkalic, trachytic types and one rhyolitic type occur as apparent plugs and crater-fillings at central vents or as dike-like masses, but in no case as a demonstrated lava flow.

As a whole the island is essentially basaltic and is structurally an elongated, exogenous dome with original dips (0° to 20°, average about 10°) of the lava flows generally to the northward on the northern slopes, and to the southward on the southern slopes. (See Plate B, sections.) In consequence the sea-cliffs are usually cut on the down-dip edges of flows and pyroclastic beds. This relation is illustrated in Plate 2, A. The lavas appear to have issued from fissures running nearly parallel to the axis of the island, and most of the loci of explosion were probably situated on these fissures. One of the eruptions took place quite recently, after a long period of erosion, during which no vent of any kind seems to have been active. This special, young flow—a limburgitic basalt—is mapped under the name of the Leone lava.

The eruptions that furnished the great bulk of the rocks above sea-level have thus been due to quiet outwelling at central vents and at fissures, and, in somewhat smaller degree, to explosion at vents of the central type. The much larger volume of rock below sea-level may represent a greater dominance of fissure-eruption, like that shown in Savaii, Upolu, Tau, or the Hawaiian Islands.

The ascertained vents of the central type include:

1. Two tuff cones, with breached craters, at Steps Point.
2. The very similar cone and crater of Aunuu Island.
3. A vent just offshore, between Utumea and Tula, at the eastern end of Tutuila—a cone which, although now nearly all cut away by the waves, may have been formed only a little time before explosions built up the Aunuu cone.
4. Older offshore vents, assumed in order to explain local, strong, landward dips in beds of lava and agglomerate east of Laulii, and again a few hundred meters east of Nuuuli, south of Matafao Peak.
5. A cliffed cone of agglomerate at Tapu Tapu islet, off the western end of Tutuila.

6. A small neck of mafic gabbro near Fagasa, west of Pago Pago.
7. Four plug-like masses of trachyte, mapped at Papatele, Afono, Vatia, and Matafao; an allied mass of quartz-trachyte or rhyolite in Pioa. These five bodies seem to have risen to the surface at as many crater openings and are thus entered in the list of central eruptions. In two of the cases, the monolithic lava has been erupted through exceptionally important, strictly localized masses of breccia; for convenience these will be called the Pioa breccia and Matafao breccia, respectively.

The basic dikes are generally narrow and pod-like, or otherwise irregular. They are numerous along the shore and presumably are about as common in the lavas and tuffs under the jungle-cover of the interior. No sill, laccolith, or chonolith was discovered.

The recent deltas, landslides, coral reefs, beaches, and spits complete the list of formations.

OLDER LAVA FLOWS AND ASSOCIATED PYROCLASTICS: BASALTS AND TRACHYDOLERITIC BASALTS.

The dominant lava flows, common basalts, vary chiefly in their content of phenocrystic olivine. Generally this mineral is much less abundant than it is in the staple lavas of Tau and Upolu. In more than half of the basaltic specimens collected it is entirely absent or quite subordinate. Herein is a noteworthy contrast with the more steadily olivine-rich quality of the dominant flows in Hawaii.

Olivine-rich flows of the older series are well represented in outcrops along the trail to the old wireless station west of Pago Pago village. There at least two such flows, separated by agglomerate, were found. One of the flows contains angular segregations or inclusions of olivine, reaching 1.5 cm. in diameter. Somewhat larger nodules of nearly pure olivine were observed in an olivine-poor, basaltic flow on the trail from Pago Pago to Vatia, near the top of the divide, on the southern slope.

Another contrast with the lava fields of Upolu, Tau, and Hawaii is found in the comparative rarity of ropy or pahoehoe flows in Tutuila, where the blocky or aa type is normal. In general, the Tutuila flows are thicker and seem to have been decidedly less fluid than was the case with the flows constituting the great Hawaiian domes. In some cases the tuff and agglomerate underlying flows have been ploughed out, and large blocks of the pyroclastic material were in this way incorporated in the flows.

At many sections the Samoan aa flows were seen to have been crushed down by the weight of the overlying rocks, whereby each aa flow as a whole has been considerably compacted. How great this effect is could not be directly measured, but judging from the condition of similar Hawaiian flows which have never been buried, the compacting has been estimated as ranging from 2 to 10 per cent of the original volume. The change of volume is due to a mechanical crushing-down of the original ragged blocks; in no case were gas-vesicles clearly seen to have been deformed by the load.

These older basalts, regularly fine-grained to dense, show the usual variations in color and phenocrystic development. Amygdaloidal fillings of the gas-pores

were seldom observed, and then seen in many cases to be only partial. Feldspar is seldom conspicuous, but on the summit of the ridge (altitude, 1,300 feet) about 1,200 meters northeast of the church in Pago Pago village, Dr. Mayor found a deeply lateritized, vesicular flow of porphyritic basalt with thin-tabular phenocrysts of plagioclase reaching 2 cm. in length. On account of its great alteration, this material has not afforded satisfactory microscopic data. This occurrence seems to be unique in the island.

Many of the buried flows of basalt are strongly reddened at top and bottom, particularly in the fractured, scoriaceous phases. This familiar phenomenon is still rather a puzzle. It is probably not due to weathering processes, operating in the intervals between successive outflows. Nor, if one may judge from the young flows of Samoa (and of the Hawaiian Islands), is the increase in ferric iron connected with the passage of steam outward from the heart of each of the reddened flows as that flow finally solidified. The depth of the reddening is in no direct proportion to the thickness of the flow concerned, and, secondly, many, if not most, young flows are not red immediately after cooling to the temperature of the air. A better hypothesis seems to be found in the idea that the reddening has been accomplished after burial of the flows, through the action of steam or water-gas working its way along the porous, scoriaceous layers from the hot, gas-charged interior of the volcanic pile. In some cases steam, caused by the volatilization of vadose water in the porous rock immediately underlying thick, hot flows, may have been an important agent; but such a purely local process seems quantitatively inadequate in explaining the red phases of the average, thin flow.

Four specimens of this older series of lavas were selected for chemical analysis.[1] A specimen (No. 2589), representative of the older basalts rich in olivine, was collected at the southern end of the sea-cliff on the east side of Fagasa Bay. This flow dips 18° north, and, like the basaltic flows above and below, is cut by a 4-foot dike of basaltic trap, vesicular in the middle. The analyzed specimen is fine-grained, dark gray, vesicular, and charged with rather abundant, slightly serpentinized phenocrysts of olivine. The compact groundmass is composed of pale-colored augite, basic labradorite, and abundant magnetite. The maximum length of the feldspar laths is little more than 0.05 mm. Apatite was not clearly determinable. An analysis of No. 2589 is given in column 1, Table 1. It has close similarity with Jensen's analysis of the Savaiian flow of 1905–6, column 2.

Specimen No. 2574, fairly typical of a large number of the Tutuila flows, was collected at the trail running eastward from Afono and on the first divide. It is a compact, dark greenish-gray trap, taken from the middle of a flow. A few small feldspars are the only phenocrysts visible macroscopically; they are plagioclase, slightly zoned, and varying from basic to acid labradorite. Granules of pale-green augite, rarer rounded grains of olivine, apatite, and much magnetite compose the typically basaltic groundmass. An analysis of No. 2574, an olivine-poor basalt, gave the results shown in column 3 of Table 1.

[1] In this paper many petrographical details will be omitted, as not appropriate in the volume of which it is a part.

A third type of flow is represented by an analyzed specimen (No. 2634), collected on the trail about 300 yards southwest of the 815-foot summit west of Aoloau village, on the north shore of the island. This flow, dipping about 4° to the northward, is trappean, compact to dense, rather light greenish-gray in color, and charged with a few small vesicles. The dominant constituents are feldspar and augite. A few small microphenocrysts of anhedral olivine were observed. Rare brown biotite and a few blades of green hornblende are accessory. The abundant iron "ore" is probably ilmenite. On account of the fine grain the feldspars are difficult to determine. Most of them appear to be labradorite near $Ab_{50}An_{50}$. These are immersed in a moderately developed mesostasis with lower double refraction, probably soda-orthoclase, which sometimes forms thin orientated shells around the labradorite. The augite is, in thin section, pale green-gray and shows strong dispersion. An analysis of No. 2634 is shown in column 4 of Table 1.

TABLE 1.—*Basalts of Samoa.*

	1	2	3	4	5
SiO_2	45.70	45.96	47.56	48.34	52.38
TiO_2	4.96	5.50	1.89	6.50	2.99
Al_2O_3	9.14	10.94	16.90	12.30	16.67
Fe_2O_3	6.38	5.85	4.23	4.38	2.80
FeO	6.73	6.39	9.08	8.06	5.68
MnO	0.20	0.08	0.33	0.06	0.07
MgO	11.88	10.82	4.63	7.63	3.39
CaO	9.90	9.96	7.26	6.73	5.58
Na_2O	2.11	2.40	4.81	3.70	4.24
K_2O	1.22	1.92	1.37	1.76	2.38
H_2O+	1.29	0.36	1.68	0.27	1.27
H_2O-	0.40	0.12	0.44	0.24	1.36
P_2O_5	0.17	n. d.	0.59	0.58	1.25
NiO	n. d.	0.02	n. d.	n. d.	n. d.
	100.08	100.32	100.77	100.55	100.06
Sp. gr.	*3.07	.....	2.91	2.87	2.75

TABLE 1.—*Norms.*

	1	2	3	4	5
Quartz	.....	.....	.....	.....	3.60
Orthoclase	7.23	11.12	8.34	10.56	14.46
Albite	17.82	18.34	31.44	31.44	35.63
Anorthite	11.68	13.24	20.57	11.68	19.46
Nephelite	.....	1.14	4.83	.....	.....
Diopside	28.51	28.08	9.87	14.10	.....
Hypersthene	9.90	.....	.....	10.60	11.67
Olivine	4.62	9.94	12.62	1.82	.....
Magnetite	7.42	4.64	6.03	6.50	4.18
Ilmenite	9.58	10.49	3.65	12.31	5.78
Hematite	1.60	2.72	.....	.....	.....
Apatite	0.34	.....	1.34	1.34	3.02
Water	1.69	0.48	2.12	0.51	2.63
	100.39	100.19	100.81	100.86	100.43

* All specific gravities given in the text were determined with the pycnometer and vacuum pump, at about 21° C.

1. Olivine-rich basalt [(III) IV. 2. (1) 2.2.2., montrealose]. No. 2589, Fagasa Bay, Tutuila, Samoa. Washington analyst.
2. Olivine basalt (III. 5.3″. 4, camptonose), Lava of 1905–06, Malaiola, Savaii. H. I. Jensen analyst. Proc. Linnean Soc. New South Wales, vol. 32, 1908, p. 706.
3. Olivine-poor basalt (II″. 5″. 3.″ 4, andose). No. 2574, east of Afono village, Tutuila. Washington analyst.
4. Olivine-poor basalt (III. 5. 2″. 4, kilauose). No. 2634, near Aoloau village, Tutuila. Washington analyst.
5. Trachydoleritic basalt (II. 5. 3. 4, andose). No. 2603, shore, 1.5 km. east of Pyramid Rock Tutuila. Washington analyst.

[F. M. Möhle (Neues Jahrb. f. Miner., Beilage Band 15, 1902, p.99) reports Dieseldorff's analysis of a mafic basalt from the island of Upolu, Samoa.]

The rock is an olivine-poor basalt, tending toward trachydolerite. Its high content of titanium oxide is remarkable—perhaps the highest known among the basalts of the Pacific region, a group of lavas which Washington has shown to be specially characterized by the abundance of this oxide.

A fourth type sampled for analysis, specimen No. 2603, was collected at a prominent sea-cliff crossed by the shore trail, 1.5 km. east of Pyramid Rock and 2.4 km. west of Amaua village, on the south shore. This rock is dense, non-vesicular, weathering into spheroidal forms. Its relations are somewhat obscure, but the mass is thought to be a flow. When first fractured, the color is slate-gray with a bluish

tinge. After a few hours a decided greenish color has been assumed; after a week or 10 days the color is a dark green-gray, markedly contrasted with the original tint. This rapidity of change of color on exposure to the air is matched in the case of the Vatia trachyte, described below.

Neither in the hand-specimen nor under the microscope are phenocrysts conspicuous, though in thin section anhedral tabular crystals of andesine, $Ab_{60}An_{40}$, surrounded by mantles of sodic orthoclase, have here and there grown a little larger than the mass of the feldspar. Such large crystals seldom reach 0.1 mm. in length. The groundmass is a very fine-grained aggregate of the same feldspar species, colorless diopside, pale greenish-gray augite, magnetite or ilmenite or both, and apatite. Neither olivine nor hypersthene were found. The analysis of No. 2603 is given in column 5 of Table 1.

The rock may be classified as a trachydoleritic basalt. Still more clearly than the last rock described, No. 2603 illustrates the transition of many of the Tutuila lavas from common basalt, through trachydolerite, to trachyte. The consanguinity of this rock with the Vatia trachyte is also suggested by the peculiar change of color on short exposure to the air, a property common to both masses.

Among the rocks of basaltic habit on Tutuila, older than the Leone flow, Weber[1] recognized the types here listed:

1. Olivine basalt, called "Feldspathbasalt."
2. Andesitic basalt, described as "in der Mitte zwischen Andesit und Basalt."
3. "Palagonittuff."
4. Trachydolerite.

Weber gives partial analyses of two of the trachydolerites.

TABLE 2.—*Trachydolerites of Tutuila.*

	1	2
SiO_2	55.78	53.15
Al_2O_3	18.12	20.76
Fe_2O_3	8.60	9.55
MgO	1.91	2.42
CaO	5.78	5.60
Na_2O	5.50	4.50
K_2O	2.62	2.21
Ignition	1.28	1.71
	99.59	99.90

1. Trachydolerite, Amaua, Tutuila. Hobein analyst. Weber, op. cit., p. 297.
2. Trachydolerite, Afono, Tutuila. Hobein analyst. Weber, op. cit., p. 300.

These two analyses are very unsatisfactory, because of their incompleteness, as in the non-determination of the two oxides of iron and of titanium and phosphorus oxides, and still more because, obviously, much magnesia has been weighed with the alumina.

Friedlaender[2] concluded that the lavas west of a line joining Nuuuli and Fagasa are considerably younger than those to the eastward. With the exception of the

[1] M. Weber, *Zur Petrographie der Samoa-Inseln*, Abhand. K. Bayer, Akad. Wiss., II Klasse, vol. 24, pp. 295–301, 1909.
[2] I. Friedlaender, *Beiträge zur Geologie der Samoainseln*, Abhand. K. Bayer. Akad. Wiss., II Klasse, vol. 24, pp. 530–533, 1910.

Leone flow, the present writer was not able to confirm this judgment definitely. Opposite Tapu Tapu islet, certain flows, forming part of a low wave-cut bench, bear in places their original ropy surfaces and are relatively young. At other points on both sides of the island, the lavas exposed in the sea-cliffs are fresh. The impression of greater youth, as compared with the lavas east of the Nuuuli-Fagasa line is, however, in part owing to the smaller proportion of pyroclastic interbeds in the western area; the tuffs and agglomerates weathering much more rapidly than the flows. Moreover, the valleys eroded in the western area are comparable in depth and width with those east of Pioa, indicating a nearly equal antiquity for the respective fields of basalt.

Every volcanologist knows the difficulty of distinguishing in the field the different types of basaltic flows for purposes of accurate mapping, which in Tutuila is rendered practically impossible by the growth of jungle. However, some notes may be added on the subject of distribution, as far as that can be determined with the aid of several scores of thin sections. The Leone limburgitic flow is specially mapped. Trachydoleritic basalt has been found about 1 km. west by south of Aoloau village, along the north shore of Leone Bay, and in the flows facing the Lion's Head, just west of Fagaitua Bay; this type is probably represented at other localities. Among the older flows of the island, highly femic olivine basalt was found in at least two flows, traversed in the trail from Pago Pago to the Radio Mast, at the 600-foot contour and again at the top of the ridge.

The common basalts include the two classes, one with abundant olivine, the other free from, or very poor in, that mineral. Olivine basalt was demonstrated at nineteen different localities, distributed through the whole length of the island (see Plate B). Principal occurrences are recorded at:

Cape Tapu Tapu.
Fagalii.
Fagamalo.
Asu.
Fagasa Bay, east side.
Vatia Bay, east side.
Afono Bay, west side.
Masefau Bay, east side.
Point next west from Kidd's Point.
Amouli Bay, west side.
Fagaitua.
Fagaitua Bay, west side.
Point between Leone Bay and Seetaga Bay.
Plateau surface north of Leone.
Cliff across Pago Pago Bay from Fago Togo.
Ridge north of Pioa.

The common basalts free, or nearly free, from olivine were found (see Plate B) at:

Agugulu.
Utumea.
Northwestern spur of the plateau north of Leone.
Malaeloa.
Tauimata Peak, northeast side.
Shore west and east of Faganeanea.
Blunts Point.
Hill slopes west and southwest of Fago Togo.
Bore-hole through the reef, just north of Blunt's Point.
Top of Alava ridge.
Hill slopes southwest, south and east of Vatia.
Trail just east of Afono.
Shore from Breakers Point to Pyramid Rock.
Fagaitua Bay, west side.
Sandy Point.

The olivine-free or olivine-poor type is thus seen to be as generally distributed over the island as the normal olivine basalt; the former is, indeed, probably somewhat the more abundant of the two.

MATAFAO TRACHYTE AND BRECCIA.

An exceedingly dense growth of pandanus, fern, etc., prevents an accurate mapping of the trachyte which crops out at the summit of Matafao, the highest point in Tutuila (Plate 2, B). From the limited exposures, this body of alkalic rock appears to represent a small pipe, penetrating massive, basaltic breccia. The breccia, thick and widespread, seems to fill a caldera-like cavity developed in the older basalts by one or more major explosions. The distribution of the breccia is indicated, though only quite roughly, on the map (Plate B). No trachytic fragments were found in the Matafao breccia as exposed in the peak itself, but along the shore at Faganeanea a number of fragments of whitish trachyte appear in blocks of otherwise similar breccia which may have slid down from the steep upper slope of the Matafao cone.

In horizontal section the greatest diameter of the trachyte pipe is probably less than 100 meters. At the surface this rock is everywhere deeply weathered and friable. The altered material was examined microscopically and seen to be practically identical with the Papatele trachyte. Like all the other Tutuila trachytes, the Matafao rock is dense to microporphyritic and non-vesicular.

Weber's description of Friedlaender's specimen applies to those collected by the present writer, who, however, did not find even one phenocryst of any dark-colored mineral, although Weber reports one phenocryst of biotite. Of the altered rock, Weber gives the following analysis (col. 1):

TABLE 3.

	1	2
SiO_2	66.03	66.19
Al_2O_3	20.52	17.45
Fe_2O_3	3.24	2.95
CaO	1.32	1.16
MgO	.....	Tr.
Na_2O	2.43	5.55
K_2O	2.47	4.90
Ignition	4.24	1.61
	100.25	99.81

1. "Phonolitic trachyte," Matafao, Tutuila. Hobein analyst. M. Weber, op. cit., p. 296
2. "Alkalitrachyt," Tafagagai, Tutuila. Hobein analyst. M. Weber, op. cit., p. 297.

The rock is clearly a trachyte, in spite of the imperfections of the material and of the analysis itself. It is hard to see why Weber decided to designate the rock as a "phonolitic" trachyte.

For convenience of tabulation the analysis of a type from a locality called "Tafagagai" is copied from Weber's paper in column 2 of the foregoing table. The present writer has been unable to place this locality on the map of Tutuila; it is probably remote from the Matafao center. Weber calls this rock an "Alkalitrachyt"; it is of a greenish-gray color.

PIOA RHYOLITE (QUARTZ-TRACHYTE) AND BRECCIA; PAPATELE TRACHYTE.

The impressive Pioa, "the rain-maker," 1,717 feet or 523 meters in height, is precipitous on all sides except on the east-southeast (Plate 1, A). It consists of monolithic rhyolite with quartz-poor phases and perhaps with quartz-free phases, erupted through agglomerate and tuff, which occupy a broad, deep depression in the older basalts. The relations are like those of the trachyte at Matafao. Just south of the Aua-Afono trail the rhyolite is in contact with the basaltic flows; elsewhere it is in contact with pyroclastics, the distribution of which is indicated on Plate B. Since there are no reëntrants in the plan of the contact, where that line crosses deep gulches, the contact at visible levels may be regarded as nearly vertical. This attitude corresponds well with a vertical jointing in the rhyolite, best displayed near the contact.

Locally the rhyolite has fluidal structure, marked by layers of differing tints and resistance to the weather, by some alignment of phenocrysts, and by slight variations of grain. At the contact on the north side, the fluidal banding dips about 50° to the eastward, crossing the joint system at an angle of about 30°. At the southern contact the banding is absent. Elsewhere it exists, as shown by talus blocks, but its relation to the contact was not determined. In some of the talus blocks, as at Aua village, the bands are contorted, and the surfaces are pitted by differential weathering (Plate 3, A).

The small body of trachyte that outcrops in the Papatele summit, southeast of Pioa, also has a fluidal structural and nearly vertical jointing (Plate 1, A). It is surrounded by the Pioa breccia-agglomerate except on the south, where it is in sharp contact with flows of basalt.

The Pioa breccia, which so nearly surrounds the two salic monoliths, is almost entirely composed of fragments of the older basalts. A few blocks of the light-gray trachyte or rhyolite are also inclosed, showing that some of the alkalic magma had already solidified before the powerful explosions ceased. Such blocks appear in fallen masses of breccia found at the shore west of Pioa and in place on the spur southeast of Pioa.

The larger body of salic rock, in Pioa, seems best regarded as a crater-filling or endogenous dome, much like the celebrated "spine" at Mount Pelée, Martinique, though of greater cross-section. The Papatele mass is probably a volcanic neck, perhaps communicating with the pipe through which the Pioa trachyte welled up, to fill the main crater.

At all outcrops the Pioa-Papatele rhyolite and trachyte are very compact and light-gray to whitish, passing into various shades of brown in the more weathered phase. The pale gray tint characterizes the rock recently exposed by slips along the joints, and to the maximum depths attainable with a sledge hammer either in the ledge or in fallen blocks. Moreover, the rock is strong and resonant under the hammer. There was at first no suspicion that light gray was not the original color. That this first impression is probably wrong is suggested by the extraordinary case of color changes displayed in the Vatia trachyte, noted below. Judging by the analogy, the original color of at least the trachytic phases at Pioa is a bluish gray,

much darker than the whitish gray of the outcrops, and passing after a few days of exposure to the air, to a deep gray-green. The color changes will be discussed in connection with the Vatia trachyte.

A few minute shreds of biotite were seen in the Papatele trachyte, but that mineral can not be rated as other than a rare accessory. Mica has not been found in the Pioa mass. Otherwise the two bodies are macroscopically similar.

The freshest specimen, procured south of the Aua-Afono trail, was selected for analysis (No. 2541), column 1 of Table 4. The rock is very compact and colored in streaks varying from gray-white to light bluish-gray and pale brown; the streakiness expresses the fluidal structure. To the naked eye no dark minerals are visible and rare glints of light betray the presence of a few microphenocrysts of alkalic feldspars. These have maximum lengths of about 2 mm., though they are rarely longer than 0.5 mm. Their optical properties are those of soda-orthoclase or anorthoclase, probably the former. A few oligoclase phenocrysts of small size were found in one thin section. A few small, anhedral grains of quartz stand out from the groundmass. The groundmass is essentially composed of soda-orthoclase (possibly anorthoclase), subordinate acid oligoclase, and anhedral quartz, with sparse, dust-like grains of magnetite. A little interstitial glass was found in one specimen from the same locality, but not in the specimen actually analyzed. Very rare granules of a mineral suggesting colorless acmite were also found; apatite seems to be quite absent. A small amount of what seems to be nearly colorless chlorite was found in one thin section. No mafic mineral whatever is essential to the rock.

TABLE 4.—*Quartz trachyte and trachyte of Tutuila.*

	1	2	3	4
SiO_2	71.20	66.13	66.85	64.71
TiO_2	.26	.61	.70	n. d.
Al_2O_3	12.82	16.82	17.23	18.40
Fe_2O_3	4.05	2.75	1.49	3.72
FeO	.28	1.69	.98	n. d.
MnO	.06	.10	ft. tr.	n. d.
MgO	.04	.47	.11	trace
CaO	.50	1.44	1.80	1.83
Na_2O	5.80	5.28	5.44	5.01
K_2O	5.30	4.46	4.49	4.20
H_2O+	.16	.38	.42	2.26
H_2O-	.09	.29	.19	
P_2O_5	none	.08	.12	n. d.
	100.56	100.50	99.82	100.13
Sp. gr	2.55	2.61	2.60	.....

TABLE 4.—*Norms.*

	1	2	3
Quartz	19.50	14.76	14.22
Orthoclase	31.14	26.69	26.69
Albite	36.68	44.54	46.11
Anorthite	.....	6.39	8.06
Corundum	.....	.92	.41
Acmite	11.09	.....	.....
Diopside	.22	.....	.....
Hypersthene	.....	1.20	0.30
Wollastonite	.93	.....	.....
Magnetite	.23	3.94	1.39
Ilmenite	.46	1.22	1.37
Hematite	.....	.....	.48
Apatite	.....	.34	.34
Water	.25	.67	.61
	100.50	100.67	99.98

1. Quartz trachyte [(I) II.4.1 3, grorudose]. No. 2541, south of Aua-Afono trail, Pioa dome, Tutuila. Washington analyst.
2. Trachyte (I″.4″.″2.(3)4, lassenose). No. 2576, near Vatia, Tutuila. Washington analyst. Fresh, green specimen.
3. Trachyte (I.4(5).2.(3)4, lassenose). No. 2580, near Vatia, Tutuila. Washington analyst. Grayish, weathered specimen.
4. Trachyte, Pola Island, near Vatia, Tutuila. Hobein analyst. Weber, op. cit., p. 300.

In one thin section a minute, interrupted veinlet of quartz shows that a small amount of this mineral has been introduced into the rock, but the analyzed speci-

men must contain from 5 to 10 per cent by weight of free, primary quartz. The rock is thus to be placed in the rhyolite family. Chemically it is nearer some comendites and some pantellerites than is common rhyolite; yet it lacks the characteristic dark-colored constituents of either comendite or pantellerite. The field habit of the Pioa mass is identical with that of the true trachytes of the island, and in fact the content of quartz is much less on the side of Pioa toward Papatele, so that the rhyolite seems to be transitional into a type which closely approximates to trachyte. Hence the old name "quartz-trachyte" might be a somewhat appropriate, alternative name for this particular rhyolite.

Some of the ferric oxide doubtless occurs in the feldspar, which is slightly tinted and distinctly dusty, but most of it must occur in the colorless, diopside-like acmite, the presence of which is shown in the norm.

During the weathering of the Pioa rhyolite, joint-planes and other fractures have been locally filled with manganese oxides, which stand out conspicuously on the pale-gray surface of the surrounding rock. Pods or knot-like segregations of braunite, coated with psilomelane (these mineral species were kindly determined by Dr. C. Palache), were also found, occupying cavities in the rhyolite at or near the surface, beneath the soil-cap. The segregation of these oxides has evidently accompanied the bleaching of the rhyolite, which in places is almost white in color. These processes have involved surprisingly little alteration of the dominant feldspathic constituents of the rock. Similar removal of manganese from the weathered phases has affected all the Tutuila trachytes. The case is paralleled by the manganese dendrites and fissure-fillings in the trachyte of the Spitzberg in Bohemia.[1]

AFONO TRACHYTE.

About 1,500 meters north-northwest of Pioa is another eroded mass of dense, pale-gray, non-vesicular trachyte. The sea has cut into it, making an imposing 200-meter cliff on the east side of Afono Bay. The contacts are not well exposed, but probably this is another filling of a volcanic neck. The surrounding rocks are, however, not breccias formed by explosions at that vent, but are the older basaltic flows and interbedded agglomerates with the northerly dips usual on the northern side of the island. From the neck a 15-meter dike of trachyte runs for a short distance toward Afono village. The high sea-cliff, weathered to bright shades of brown and red, shows again the platy flow-structure—here dipping about 50° to the east-southeast; as at Pioa, the flow-structure is crossed by a nearly vertical system of joints.

VATIA TRACHYTE.

The highly picturesque Pola (Cockscomb) Island is a huge sea-stack, cut out of the largest body of trachyte exposed in Tutuila (Plate 3, B). Its general shape is quite vividly expressed by its alternative name. The total length of the trachytic mass, as exposed, is about 3 km.; how far it continues under water, beyond Pola Island, is unknown. The maximum width is about 500 meters. Like the Afono body, this trachyte cuts the older basalt flows and seems not to be surrounded

[1] See F. Becke, Tschermak's Min. Petrog. Mitt., vol. 33, 1915, p. 525.

with breccias dating from its own eruptive epoch, though locally many basaltic blocks are inclosed in it. Like most trachytes the world over, the Vatia rock is not vesicular in the sense of being charged with bubble-shaped cavities. As is usual with trachytes, the absence of such vesicles gives no indication whether the mass is intrusive or extrusive; it may be a wide dike or a thick flow. If the latter, erosion has completely destroyed the constructional form and, as well, the very thin pumiceous shell which often covers the initial surface of a trachytic flow.

At most outcrops the Vatia rock is almost indistinguishable from the Pioa rhyolite (Plate 4, c). Here also are found whitish, pale matt-gray, and brown colors; a fractured contact phase veinleted with manganese oxide; a platy, fluidal structure; and a more or less vertical jointing.

A remarkable characteristic is the very rapid change of color when the perfectly fresh Vatia trachyte is first exposed to the air. The color is at first a bright bluish-gray, quite different from the duller, earthy gray of the normal, slightly weathered outcrop. Three hours after the fracture was made, the tint was already deepened, and a greenish tinge had replaced the blue (Plate 4, A and B). After 2 days the color has become a strong gray-green, which continues to deepen, so that after 6 months or more the change is seen to have affected the rock to a depth of several millimeters. The behavior is analogous to that observed in a compact lava on the south shore and to a less striking change in the case of a trachyandesite dike which is described on a following page.

These three Samoan instances of rapid color-change are matched by four others already noted in print: syenite and paisanite of Ascutney Mountain, Vermont; a syenite near Loon Lake, New York State; and a common phase of the well-known Quincy granite of Massachusetts.[1] Five of these six rocks are strongly alkalic, and in every case the color change seems to be due to reactions affecting constituents of, or inclusions in, the feldspars. Special experiments referred the change in the Ascutney rocks to oxidation. The simpler of these tests were applied to both the Samoan types, with a similar conclusion. In an oxidizing flame the color change is almost instantaneous, showing that no organic substance is involved. No decisive evidence has yet been found as to the nature of the sensitive ingredient in the feldspars. The feldspar of the Ascutney syenite is charged with dust-like particles of some indeterminable material, speculatively considered to be free ferrous oxide, which would be oxidized on exposure to the air. Inclusions of the same kind are not visible in the Samoan feldspars, thin sections of which throw no clear light on the problem. The question remains open, though the writer is inclined to look for the cause of color change in the presence of an unstable iron or manganese compound.

Weathering, continued long after the green tint was established, has bleached the trachyte. In this process the superficial layer of the rock-ledge, to a depth of several decimeters, has become colored in alternating shells of white and rather deep brown, suggestively like "Liesegang" rings when the shells are viewed in section.

[1] R. A. Daly, Bull. 209, U. S. Geol. Survey, 1903, pp. 52, 74; H. P. Cushing, Bull. Geol. Soc. America, vol. 10, 1899, p. 178; C. H. Clapp, Bull. 704, U. S. Geol. Survey, 1921, p. 72.

A specimen (No. 2576) of the almost perfectly fresh green phase, taken at the shore opposite Pola Island, was selected for analysis; the result is given in column 2 of Table 4. Its rare phenocrysts of feldspar reach maximum lengths of about 7 mm. Some of these are zoned, with cores of basic oligoclase, surrounded by thin shells of soda-orthoclase and also shells of albite. Phenocrysts of pure orthoclase were not observed, nor any composed of the labradorite-bytownite mixture, reported by Weber in this rock. The only other phenocrysts are extremely rare biotites, 5 to 8 mm. in diameter; these are ragged and show evidence of resorption.

The groundmass is a very fine-grained, microcrystalline aggregate of dominant orthoclase (apparently strongly sodiferous) and oligoclase, with decidedly subordinate shreds of greenish-brown biotite, which are commonly bleached around the edges. Magnetite, a little apatite, and zircon(?) are accessory. Secondary minerals, calcite, chlorite, and limonite, are of almost negligible importance. The rock is a (biotite) trachyte relatively rich in alkalies and very poor in mafic minerals.

A specimen (No. 2580) of the thick, gray-white, weathered phase, from the same locality as No. 2576, was analyzed (see column 3, Table 4). The bleaching of the rock to such great depths has been facilitated by its porosity. This alteration has not perceptibly affected the feldspars except by the removal of some of the ferruginous matter disseminated through them; otherwise the dominant constituents seem to be as fresh as in specimen No. 2576. The bleaching of the biotite has gone much further than in No. 2576.

Comparison of the two analyses of this rock (columns 2 and 3, Table 4) shows that the decoloration has been associated with the removal of iron and manganese oxides. The silica has not been significantly increased, nor could free quartz be demonstrated in the weathered phase. This fact strengthens one's scepticism that the free quartz in the Pioa rock, macroscopically and mineralogically so like the Vatia trachyte, could have been introduced during the progress of ordinary weathering. No quartz-bearing phase was found anywhere in the Vatia mass.

LEONE LAVA (LIMBURGITIC BASALT).

The Leone lava, described by Weber and Friedlaender as limburgite, covers an area of nearly 20 square kilometers. The fissure or fissures from which it flowed could not be closely located on account of the cover of jungle, but it is clear that one vent is situated in the valley running north from Maupasaga village, and probably about 1 kilometer from the village. Only one period of eruption appears to be represented in the area mapped as covered by the Leone lava, and there is no evidence of more than one flow. The thickness of the lava is clearly more than 10 meters near Maupasaga and it may be 70 meters or more in the area where the flow overwhelmed the Tutuila shelf. The lava flow not only filled the old lagoon but also buried the drowned barrier reef. The waves are now cutting cliffs and chasms, and there are many fine spouting-horns in the upper part of the lava flood (Plate 2).

The characteristically ropy surface of the lava is usually very fresh, yet the flow is already old enough to support a growth of trees of which the trunks reach a meter or more in diameter (Plate 5, B). The eruption took place not many thou-

sands of years ago. Its abundant vesicles have not yet been filled with mineral matter.

A typical specimen of the lava (No. 2557), collected at the road 1.5 km. northwest of Tafuna, was selected for analysis. It is dark gray in color, highly vesicular, and richly charged with olivine phenocrysts, reaching diameters of 1 to 2 mm. Smaller phenocrysts of augite are visible in thin section. These are immersed in brown glass, which also contains laths of acid bytownite, $Ab_{25}An_{75}$, and a high proportion of ilmenite and magnetite in grains and skeleton crystals. No other mineral could be surely identified, though a little apatite is probably present. The mean of two Rosiwal determinations, made from different specimens, has furnished a rough idea of the mode. The percentages by weight are as follows: Augite, 35; olivine, 12; bytownite, 9.3; ilmenite and magnetite, 8; apatite, 0.7; glass, 35; total, 100. The results of the chemical analysis are shown in Table 5, which also gives an analysis of the 1905–6 flow at Matavanu, Savaii. The similarity is striking, but compare column 2, Table 1 (page 102).

TABLE 5.—*Limburgitic basalt.*

	1	2
SiO_2	43.63	43.76
TiO_2	5.30	3.41
Al_2O_3	11.70	11.58
Fe_2O_3	1.82	4.39
FeO	9.43	7.57
MnO	.16	n. d.
MgO	10.87	12.97
CaO	11.40	9.64
Na_2O	2.57	3.03
K_2O	1.63	1.84
H_2O+	1.19	.47
H_2O-	.08	.....
P_2O_5	.58	.45
	100.36	99.78
Sp. gr	3.10	3.032

TABLE 5.—*Norms.*

	1	2
Orthoclase	9.45	11.12
Albite	8.38	9.43
Anorthite	15.57	12.79
Nephelite	7.38	8.52
Diopside	29.90	24.97
Olivine	14.56	18.00
Magnetite	2.55	6.50
Ilmenite	10.03	6.54
Apatite	1.34	1.01
Water, etc	1.27	1.14
	100.43	100.02

1. Limburgitic basalt (III″.″6.3.4, limburgose). No 2557, near Tafuna, Leone lava, Tutuila. Washington analyst.
2. "Nephelite basalt" (III(IV).6.2(3).4, monchiquose). Flow of 1905-06, Matavanu volcano, Savaii. Heusler analyst. A. Klautsch, Jahrb. Preuss. geol. Landesanst., vol. 28, p. 174, (1907) 1910. Includes: CO_2 0.38, SO_3 0.14, S 0.15.

LEONE TUFF.

The two breached cones at Steps Point culminate at points 510 and 526 feet above sea. From the native names of these ridges the western center of explosion may be called the Seumalo crater, and the eastern, Logotala crater. The maximum depths of the crater floors below sea-level are 36 fathoms and 38 fathoms, respectively, though opposite each crater the 100-fathom isobath bends in strongly.

Each cone is entirely tuffaceous, no lava flows being interbedded with the tuff, which rests directly on the Leone basalt. The well-stratified tuff dips centrifugally from each crater at angles varying from 4° or less to 30°, with an average of about

12°. The dip rapidly flattens outwards, and is reversed on the north, along the road from Leone to Vaitogi. The reversal of dip is connected with the thinness of the tuffaceous layer at distances of a kilometer or more from either crater. At this distance the tuff was originally only a few centimeters to a meter or two in thickness, and it was molded on the fresh Leone lava, which dips 3° to 5° to the southward.

The igneous constituents of the tuff seem to be wholly of the nature of common basalt, already somewhat altered by weathering. These fragments are brown glass, porphyritic olivine basalt with glassy base, and holocrystalline basalt. As noted by Weber, some of the glass has the look of palagonite. Pieces of coral and reef limestone are sparsely disseminated through the igneous material, but they can hardly make up 0.1 per cent of the tuff as a whole.

The tuff is stratified to an extraordinary degree of perfection (Plate 5, A). The brown strata, varying in tint and in grain, have thicknesses that range from a millimeter to several meters, the maximum visible in crater-wall or sea-cliff. Perfect as the bedding is, it is not the product of sorting in agitated lake-water or sea-water, but is to be explained by the succession of explosions and the rhythmical raining of débris which fell from the volcanic clouds, as these were swayed about by winds and by the tumultuous outbursts of gas.

In spite of its thinness and freedom from burial, this subaerial tuff is everywhere well lithified. The hardening of each layer seems to have taken place immediately after its material fell to earth. The topmost layer is about as well consolidated as the deepest layers observed in the craters; the writer found no loose ash, such as might be expected on the surface if pressure were important in the lithification.

The reactions leading to the cementation of tuffs during actual eruptions need investigation. For lack of such direct observations, the inferences derived from a study of the Leone tuff are liable to error. The hardening may have been brought about by processes similar to those involved in the setting of Portland cement. It may be noted, however, that the microscope shows the cement to be ferruginous, essentially limonitic. A leading question attaches to the state of the iron before it was finally oxidized and hydrated. The small amount of chlorine in basaltic magma forbids the idea that the chief compound oxidized was iron chloride. On the other hand, Gautier's experiments lead to the supposition that the initial compounds involved may have been one or more of the sulphides of iron. For example, at high temperature iron monosulphide is formed by the interaction of hydrogen sulphide and magnetite.[1] One may conceive a rapid oxidation of the monosulphide in the falling ash, thoroughly wetted during the heavy rains which usually accompany volcanic explosions within the tropics. The subject needs, however, the attention of the geochemist, who will discuss the complex reactions in the volcanic cloud and in the débris showered about an explosive vent.

Along the shore south of Leone, the thin cover of tuff is so involved with the Leone pahoehoe flow as to suggest a molten state for the interior of the flow when at least some of the volcanic mud was falling. The evidence is seen in the local superposition of the ropy surface-shell of the lava on well-bedded tuff. Local over-

[1] A. Gautier, Comptes Rendus, vol. 143, 1906, p. 7.

thrusting of the lava crust would explain this relation. Again, about 500 meters east of Leone, on the road to Pago Pago, a pressure-ridge in the Leone lava is covered by about 3 meters of the thin-bedded tuff, which is conformable with the arch in the lava flow. The simplest interpretation is that the lava was still somewhat mobile when the wet ash was being showered. Neither kind of evidence is, however, absolutely conclusive.

AUNUU CONE AND CRATER.

About two-fifths of Aunuu Island is a cultivated plain, on which are a village and its taro plantations. The plain is backed by a young tuff-cone and rimmed elsewhere by a wide storm-beach, composed of coral heads and coral sand. Inside the storm-beach and a meter or two lower is a broad flat, underlain by peaty soil and volcanic sand and gravel. The latter seem to represent a slightly emerged spit, such as might be expected to leeward of the cliffed cone. The originally swampy, inner flat has been drained for cultivation, and on its surface the ditches are flanked by pavements composed of coral heads. The corals have probably been transported by man from the storm-beach; no evidence that any occur below the peaty soil of the flat itself could be found. However, the time allowed for the examination of the island did not permit of a final conclusion that the shore was not fringed with growing corals when the spit was formed. Coral patches are now thriving in the shallow water just outside the storm-beach.

The highest point of the crater rim is about 310 feet above sea-level. The floor, containing a small, fresh-water pond, is not far from sea-level. On the crater rim and in the sea-cliffs, the tuff beds show the usual quaquaversal dips and also the truncation of beds by explosion (Plate 6, A and B). The layers so truncated are covered by discordant, well-bedded tuffs which in general have centripetal dips and represent the weaker explosions of the closing eruptive stage. The tuff fragments are basaltic, except a few limestone fragments discovered by Chamberlin.[1]

Friedlaender mapped the Aunuu tuff as of "submarine origin," for which he gives no proofs in his text. The present writer found no indication of an origin different from that of the Steps Point cones, which are regarded as having been formed subaerially. No certain lava flow was found in this island, though one flow may be the source of numerous boulders of lava concentrated at one point in the crater. Friedlaender may have referred to this when he described the occurrence of one flow in Aunuu. Weber's description[2] of a specimen is that of a spilitic trachydolerite, with the following composition: SiO_2, 53.30; Al_2O_3, 21.10; Fe_2O_3, 8.90; MgO, 2.44; CaO, 5.45; Na_2O, 4.81; K_2O, 1.97; Ignition, 2.25; total, 100.22.

FAGASA GABBRO.

On the divide about 300 meters south of the Pago Pago-Fagasa trail is, with the exception of one dike, the only mass of rock with plutonic habit in Tutuila (Plate B). The thick jungle prevented a complete study of the structural relations, but the body seems to be a typical, massive volcanic neck. It is elliptical, with

[1] R. T. Chamberlin, paper in this volume.
[2] Trachydolerite, Aunuu Island, Samoa. Hobein analyst. Weber, op cit., p. 302.

diameters of from 100 to 200 meters. On all sides the neck is seen to cut across the older series of basalts. The main part of the neck is a medium-grained gabbro, which, on the north side, passes into a contact phase, about 15 meters in width and constituted of a holocrystalline basalt porphyry. The transition of gabbro into porphyry is rapid. Elsewhere the contact phase is not exposed. The granular, gabbroid, phase was selected for analysis.

The fresh rock (No. 2588) is speckled and of a greenish-gray color in the mass. Abundant green augite, in crystals up to 1 mm. in length; olivines of similar dimensions; and basic labradorite, $Ab_{30}An_{70}$, are the essential constituents. The mafic constituents are highly idiomorphic against the feldspars; well-crystallized ilmenite and apatite are the accessories. Weber reports some nephelite in a specimen which apparently was derived from the same mass as No. 2588, but none has been detected by the present writer in any one of his six specimens. The rock-powder is moderately magnetic when tested with a common hand magnet; hence some magnetite is probably present. The augite shows high dispersion. A rough determination of the mode was made, with the following result, in percentage by weight: Plagioclase, 44.6; olivine, 24.7; augite, 24.0; ilmenite and magnetite, 6.0; apatite, 0.7; total, 100.

TABLE 6.—*Gabbro of Tutuila.*

	1	2
SiO_2	45.37	44.66
TiO_2	4.84	6.60
Al_2O_3	10.51	15.42
Fe_2O_3	2.25	14.40
FeO	11.35	n. d.
MnO	.11	n. d.
MgO	13.04	5.20
CaO	8.63	9.21
Na_2O	2.29	2.44
K_2O	.94	1.02
H_2O+	.12	1.56
H_2O-	.09	
P_2O_5	.29	n. d.
S	.09	n. d.
Cr_2O_3	.14	n. d.
NiO	trace	n. d.
	100.06	100.51
Sp. gr.	3.12	.....

TABLE 6.—*Norms.*

	1
Orthoclase	5.56
Albite	19.39
Anorthite	15.57
Diopside	20.24
Hypersthene	4.49
Olivine	21.11
Magnetite	3.25
Ilmenite	9.27
Chromite	.21
Apatite	.67
Water, etc.	.54
	100.30

1. Olivine gabbro (III".5.3.4, camptonose). No. 2588, Fagasa, Tutuila. Washington analyst.
2. "Nephelite basanite" (gabbro?). Fagasa, Tutuila. Hobein analyst. Weber, op. cit., p. 301.

The rock is a highly mafic olivine gabbro, chemically much like the Leone limburgitic basalt. An analysis of No. 2588 is given in column 1, Table 6. Column 2 gives the analysis of Weber's granular rock from "Fagasa." Weber reports that a little nephelite is present in the rock represented in column 2; hence his name nephelite basanite. Hobein's analysis is very poor; it is evident that much of the

magnesia was weighed with the alumina, and that most of his "Fe_2O_3" is FeO. Hobein's "TiO_2," which was probably determined by precipitation by long boiling, is high.

DIKES: BASALTS AND TRACHYANDESITE.

About 40 dikes were recorded in the shore-cliffs of Tutuila; many more were not specially noted in that belt, favorable to observation; an indefinitely large number must exist under the cover of jungle and laterite of the interior. As in Ofu and Olosega, the majority are nearly vertical and strike along the main axis of the island; nevertheless, a considerable percentage of the dikes trend at high angles to the island axis. Generally they are short, pod-shaped or lenticular, and resemble the many dikes so admirably displayed in the high cliffs of Olosega. Examples may be well seen along the shores at the western end of Tutuila, on the north side of Leone Bay, at Pyramid Rock, in Pago Pago, Fagaitua, Amouli, and Afono Bays, and south of Cape Matatula. An extensive body of non-vesicular, compact trap crops out on the shore just north of the observatory at the entrance to Pago Pago Bay. Very similar rock was crossed for about 250 meters along the bed of Fagalua stream, not far below the Fago Togo reservoir. These two masses may represent a single intrusive, dike-like body, but the jungle prevented a satisfactory test of this hypothesis.

Most of the dike-rocks are basaltic, ranging from olivine-poor types to olivine-rich, almost picritic, types, thus corresponding chemically with the dominant lava flows. The structure is usually that of a slightly porphyritic trap. A few of the dikes have the composition and structure of olivine diabase. On the south shore, about 1 kilometer east of Tapu Tapu Islet, a poorly exposed, but wide, dike is a medium-grained gabbro, moderately rich in biotite. Andesitic dikes of any kind were not positively identified. The dike of trachyte near Afono has already been mentioned.

An unusually wide and persistent dike, running east and west, cuts the Pioa breccia along the west-flowing stream which heads between Pioa and Papatele. Its maximum width is more than 14 meters and it was followed from the 200-foot contour, at a point about 300 meters south of Aua village, eastward to the 700-foot contour, where the dike narrows to 2 meters. A specimen of it (No. 2662) is a very dense trap, dark slate-gray on a perfectly fresh fracture. After 3 hours this color attained a greenish cast; after a week's exposure to the air the color became a dull gray-green. This behavior is thus analogous to that of the basaltic lava, No. 2603, and of the Vatia trachyte, though the change is here not so striking.

There are no phenocrysts. Under the microscope the rock is seen to be composed of plagioclase (basic andesine to oligoclase-andesine) in a mesostasis of orthoclase or soda-orthoclase, which in some cases forms orientated shells around the plagioclase crystals; together with anhedral augite, the only other essential constituent, some (probably titaniferous) magnetite, and apatite. An analysis of No. 2662 gave the results shown in column 1, Table 7.

In the Rosenbusch classification the rock falls in the class of the trachyandesites. Chemically and modally it supplies another link between the highly

salic trachytes and the common basalts of Tutuila. Here again, the pronounced change of color on brief exposure to the air points to the probability of close genetic connection between the transitional species and the strongly salic trachyte. Weber's "trachydolerite" from Amaua, Tutuila (column 2, Table 7), is chemically very similar to the Aua rock.

TABLE 7.—*Trachyandesite.*

	1	2
SiO_2	56.81	55.78
TiO_2	2.28	n. d.
Al_2O_3	16.62	18.12
Fe_2O_3	3.25	8.60
FeO	4.67	n. d.
MnO	.07	n. d.
MgO	2.37	1.91
CaO	4.41	5.78
NaO_2	6.28	5.50
K_2O	2.06	2.62
H_2O+	.39	1.28
H_2O-	.66	
P_2O_5	.72	n. d.
	100.59	99.59
Sp. gr.	2.74	

TABLE 7.—*Norms.*

Norm of 1.	
Quartz	1.26
Orthoclase	12.23
Albite	53.45
Anorthite	10.84
Diopside	5.16
Hypersthene	6.15
Magnetite	4.64
Ilmenite	4.41
Apatite	1.68
Water	1.05
	100.87

1. Trachyandesite (II.5.2.4″, akerose). No. 2662, dike, near Aua village, Tutuila. Washington analyst.
2. Trachydolerite, Amaua, Tutuila. Hobein analyst. Weber, op. cit., p. 297.

GENERAL PETROLOGY.

Throughout the Samoan chain of volcanoes as a whole the dominant rock is olivine basalt. This fact appears as a result of studying the writings of Friedlaender, Jensen, Klautsch, Möhle, and Weber. The observations of 1919 confirm it. Olivine-rich basalts seem to be relatively more abundant in all the other Samoan Islands than in Tutuila itself, yet even in Tutuila they rank in importance just after the olivine-poor to olivine-free basalt. Types transitional between these common basalts and true trachydolerites are probably the third group of lavas in Tutuila, rated in terms of volumetric importance. The trachytes come fourth in the series. So far as known, rhyolite or quartz-trachyte is represented only in phases of the Pioa dome; and trachyandesite has been found in one thick dike only.

More or less closely similar associations of lavas, considered both qualitatively and quantitatively, are very common at centers of basaltic eruption on continents and in ocean basins. There must be a general law governing their evolution. The petrogenic problem of Tutuila is thus a problem of world-wide scope. Space fails here for its systematic discussion, but a few remarks may be added to show that the geology and chemistry of Tutuila tend to support a theory of origins which is increasingly favored by petrologists.

For convenience, all of Dr. Washington's analyses are stated together in Table 8.

The close chemical resemblance of the oceanic and continental basalts of both hemispheres is one of the most significant facts of petrology. In spite of manifest, drastic differentiation in these Pacific islands, the principle can once more be illustrated by a comparison between the average visible basalt of Tutuila with analogous averages of Hawaiian basalts, with the average plateau basalt, and with the average world basalt. Such comparison has now been made easily possible through the skilled labors of Washington.

TABLE 8.

	1	2	3	4	5	6	7	8	9	10
SiO_2	43.63	45.37	45.70	47.56	48.34	52.38	56.81	66.13	66.85	71.20
TiO_2	5.30	4.84	4.96	1.89	6.50	2.99	2.28	.61	.70	.26
Al_2O_3	11.70	10.51	9.14	16.90	12.30	16.67	16.62	16.82	17.23	12.82
Fe_2O_3	1.82	2.25	6.38	4.23	4.38	2.80	3.25	2.75	1.49	4.05
FeO	9.43	11.35	6.73	9.08	8.06	5.68	4.67	1.69	.98	.28
MnO	.16	.11	.20	.33	.06	.07	.07	.10	tr.	.06
MgO	10.87	13.04	11.88	4.63	7.63	3.39	2.37	.47	.11	.04
CaO	11.40	8.63	9.90	7.26	6.73	5.58	4.41	1.44	1.80	.50
Na_2O	2.57	2.29	2.11	4.81	3.70	4.24	6.28	5.28	5.44	5.80
K_2O	1.63	.94	1.22	1.37	1.76	2.38	2.06	4.46	4.49	5.30
H_2O-	.08	.09	.40	.44	.24	1.36	.66	.29	.19	.09
H_2O+	1.19	.12	1.29	1.68	.27	1.27	.39	.38	.42	.16
P_2O_5	.58	.29	.17	.59	.58	1.25	.72	.08	.12	None
	100.36	[a]100.06	100.08	100.77	100.55	100.06	100.59	100.50	99.82	100.56
Sp. gr.	3.10	3.12	3.07	2.91	2.87	2.75	2.74	2.61	2.60	2.55

[a] No. 2 contains 0.14 Cr_2O_3, S 0.09, NiO a trace.

1. Limburgitic basalt, flow, at road 1.5 km. northwest of Tafuna.
2. Mafic olivine gabbro, neck, east of Fagasa Bay.
3. Olivine-rich basalt, flow, Fagasa Bay.
4. Olivine-poor basalt, flow, near Afono village.
5. Olivine-poor basalt, flow, near Aoloau village.
6. Trachydoleritic basalt, flow, shore, 1.5 km. east of Pyramid Rock.
7. Trachyandesite, dike, 350 meters south-southeast of Aua village.
8. Trachyte mass, near Vatia village, quite fresh.
9. Same rock as No. 8, decolorized by weathering.
10. Quartz-trachyte or rhyolite, dome or crater-filling, Pioa.

An estimate of the relative volumes of the Tutuila rocks exposed above sea-level shows that the average of five of their analyses gives a near approximation to the mean composition of the basalts in this island. That average is shown in column 1 of Table 9. In column 2 is Washington's calculated average of the composition of the rocks of the great Mauna Kea cone of Hawaii—another extinct volcanic complex, comparable in total area and height to the whole ridge of Tutuila. The similarity is very striking and extends even to the mean densities. The average basalt of Hawaii (column 3) is a little different, as might be expected, but the smallness of that difference matches the field observation that in Hawaii, as in Samoa, differentiation of the basalt has not been thoroughgoing except temporarily and at a few local centers.

Already one seems justified in assuming as little variation in the average basalts of the Society, Juan Fernandez, Galapagos, and other archipelagoes of the open

Pacific, as in those of Ascension, Saint Helena, Réunion, Mauritius, and other islands of the open Atlantic and Indian oceans. The many analyses of continental basalts tell the same story.

TABLE 9.

	1	2	3	4	5
SiO_2	48.44	48.69	49.04	49.35	49.87
TiO_2	4.29	2.55	2.92	2.59	1.38
Al_2O_3	13.27	14.90	13.64	14.05	15.96
Fe_2O_3	4.06	3.79	2.99	3.40	5.47
FeO	8.27	8.14	8.89	9.94	6.47
MnO	.15	.16	.12	.21	.32
MgO	8.21	7.19	8.53	6.36	6.27
CaO	7.72	9.34	9.52	9.73	9.09
Na_2O	3.47	3.47	3.00	2.90	3.16
K_2O	1.55	1.29	.86	1.00	1.55
P_2O_5	.57	.48	.49	.47	.46
	100.00	100.00	100.00	100.00	100.00
Sp. gr	2.934	2.969	2.946	.....	.....

1. Average of 5 analyses of Tutuila basalts, given in Table 8, columns 2, 3, 4, 5, and 6.
2. Average of 12 analyses of rocks from Mauna Kea, Hawaii (H. S. Washington, Amer. Jour. Science, vol. 6, 1923, p. 361).
3. Average of 54 analyses of mafic rocks in Hawaii, weighted as follows: equal weights given to respective averages of 12 analyses from Kohala, 12 analyses from Mauna Kea, 6 analyses from Hualalai, 13 analyses from Kilauea, and 11 analyses from Mauna Loa. (See H. S. Washington, same reference as under 2.)
4. Average of 50 analyses of plateau basalts, including: 11 Deccan basalts, 6 Oregon basalts, and 33 Thulean basalts (from H. S. Washington, Bull. Geol. Soc. America, vol. 33, 1922, p. 797).
5. Average of 198 analyses of basaltic rocks, published before the year 1910; world-wide distribution (from R. A. Daly, *Igneous Rocks and Their Origin*, 1914, p. 27).

NOTE.—All averages calculated as water-free and to 100 per cent.

Such chemical uniformity, the geological evidence that basalt is primary and not itself a differentiate of some other magma developed in post-Cambrian time, and the world-wide distribution of common basalt, strongly suggest an origin of all visible basalts in a general substratum below the earth's heterogeneous crust. The comparative uniformity of the material erupted from the substratum further indicates the high probability that this world-circling shell was differentiated from the materials of the primitive earth when the globe was molten at the surface. Ever since that early differentiation, which was controlled by gravity and densities, the basaltic shell, itself little or not at all changed, has been eruptible where the integrity of the crust has been completely broken by fissures. After injection into the crust, however, the basaltic magma has been capable of differentiation under certain conditions. The segregation of the overlying, largely granitic shell to form the upstanding continental plateaus has bared the substratum which now essentially forms the crust under the deep oceans. The basalt now being erupted on the sea-floor may, therefore, differ slightly from the basalt now being extruded on the surfaces of the continents; theoretically the former should be a little richer in the heavier oxides. In spite of their great height, the Pacific volcanoes do, indeed, seem to carry somewhat more olivine per unit of volume than the basaltic volcanoes of the continental areas. Yet a definite conclusion as to the degree of chemical

variation of the basaltic substratum horizontally can not be reached until much more geological mapping and chemical analysis have been done.

Meantime, an approximate idea of the composition of the substratum may be obtained from that of the average plateau basalt which has been quickly erupted, so that the likelihood of contamination with dissolved crust-material and of differentiation is reduced, in each case, to a minimum. Recently Washington has assembled the data bearing on the chemical nature of plateau basalts. From his table an average composition has been calculated and entered in column 4 of Table 9.

For comparison the computed average for the world basalt, largely made from analyses of basalts from central vents, is entered in column 5 of the same table. This average is not very different from that for Tutuila or Mauna Kea, which, like most basaltic vents of the central type, show some differentiation of the primitive basalt. In these cases it is obviously difficult to evaluate accurately the departure of the computed averages from the composition of the original basalt. The departure can not be very pronounced.

That a fissuring of the sub-Pacific crust and tapping of the substratum actually initiated the growth of the Samoan chain of volcanoes has already been inferred. The problem of the ascensive force and that of the conditions under which the highly rigid and viscous material of the substratum can become eruptible at the base of a fissure through the earth's crust are subjects much too broad for treatment in this paper, even if their satisfactory treatment were possible in the present state of geophysics. In spite of difficulties, the assumption that the alignment of the Samoan volcanoes means abyssal fissuring seems to be the best clue to the origin of these vast bodies of lava.

The basaltic-substratum hypothesis implies that, since late pre-Cambrian time, all other igneous rocks have been formed as differentiates of basalt, as syntectics of basalt and crust rocks, as differentiates of these syntectics, or as products of the local remelting of the crust. Such remelting may be due to special depression of the crust rocks, during diastrophic processes, or to local fluxing by hot gases which have emanated from the deep interior of the earth. Since the sub-Pacific crust is probably itself basaltic in chemical composition, one is inclined to look to the differentiation of basaltic magma for the origin of most of the non-basaltic types in the Pacific volcanoes.

The list of localities, at each of which trachyte and common basalt have been successively or even alternately erupted at the same center, is steadily increasing. As in Samoa, Hawaii, Juan Fernandez, San Ambrosio-San Felix, Réunion, Ascension, Madeira, Azores, and other islands, as well as at many centers on the continents, the trachyte is greatly subordinate to the basalt in volume. In each of several known cases the same vent has delivered to the earth's surface: first common basalt and then trachyte, followed in its turn by common basalt—all within a small fraction of a single eruptive period.

With the basalt and trachyte are associated lavas which are chemically and mineralogically intermediate between these two types, and limburgitic or picritic lavas are also represented in the individual complexes. Tutuila illustrates these rules.

The quantitative, structural, and temporal relations of such rock-types of subordinate volume strongly suggest that all have been differentiated from basalt itself. This hypothesis is gaining adherents among petrologists, especially since Bowen has further elaborated the old theory of magmatic differentiation by fractional crystallization. To his writings the reader may be referred for details of the mechanism.[1] Suffice it here to note that, according to the theory, trachytic magma represents the mother-liquor left after the sinking away of the crystals which first form in a cooling basaltic solution or melt.

An important consideration, apparently not emphasized in any published discussion of fractional crystallization, may be briefly outlined. The fall of temperature, responsible for the fractional crystallization of a column of basaltic magma, has usually been assumed to be uniform at a given horizontal section of the magma. During most of the period of cooling, therefore, the residual liquid is supposed to remain unmoved. Since, however, the fall of temperature must actually be most rapid at the periphery of the magmatic chamber, fractional crystallization must be well under way before the central magma of the chamber has been similarly affected. The density of the residual liquid along the contacts is less than the density of the central magma, so that the more salic liquid must tend to rise toward the top of the chamber, being displaced by the laterally-moving, heavier magma from the central region. Thus, apparently, differentiation by fractional crystallization should be conceived as taking place by a kind of convection, which involves the steady vertical transfer of *liquid* as well as the sinking of crystals.

This addition to the speculative elements of the general theory seems to have practical importance, since it helps to explain the not uncommon case where nearly or quite typical basalt is erupted through a trachytic mass, very soon after the solidification of the trachyte. In such instances the younger basaltic flows may be regarded as emanations from the central part of the chamber magma, not yet cooled to the temperature of important differentiation, nor essentially modified by reaction with sunken crystals.

At both Pioa and Matafao the rise of salic magma was preceded by violent explosions, with the formation of large masses of breccia around those centers. In general, the world over, trachytic eruptions are heralded by extraordinarily powerful explosions. The rule suggests the accumulation of magmatic gases, under competent plugs, during the process of trachytic differentiation at central vents. The concentration of gases may itself aid in the separation of highly alkalic phases from primary basalt. To what extent these gases are resurgent (absorbed from the country-rocks surrounding the vents) is an important question, still without a satisfactory answer. Among the resurgent gases of possible importance are steam or water vapor and carbon dioxide, the former derived from wet sediments or deep-seated, wet volcanic beds, the latter derived from carbonate-bearing rocks in depth. The absorption of carbonate-bearing rocks by basaltic magma seems to be a probable condition for the generation of many, comparatively rare, "alkalic" rocks, which

[1] N. L. Bowen, Jour. Geol. vol. 23, Supp., pp. 1–91; vol. 27, 1919, pp. 393–430; vol. 30, 1922, pp. 177–198, and 513–570: Amer. Jour. Sci., vol. 39, 1915, pp. 175–191; vol. 40, 1915, pp. 161–185. Also R. A. Daly, Jour. Geol., vol. 16, 1908, p. 401.

have been differentiated from the syntectic. For the Tutuila and many other trachytes there is no direct evidence of such carbonate control over the differentiation. The absorption of exotic water by the primary basalt is doubtless more readily postulated; the whole submarine part of the Samoan volcanic ridge must be charged with interstitial sea-water. On the other hand, the country-rocks of several vents on the continents, where trachytes have been erupted on a large scale, are not specially wet. Examples are seen in Somali Land and the Great Rift region of Africa. Hence the hypothesis that trachytic differentiation is controlled by the absorption of exotic water faces a difficulty.

The conclusion is that the relative importance of juvenile and resurgent gases is not to be readily discerned. At the same time the participation of magmatic gases of whatever origin in the formation of trachyte from primary basalt appears to be possible. The differentiation of pyroxene andesite from primary basalt must take place under different conditions. Difference of gas-content, as well as difference of temperature, may be one of the causes for the contrasted products. With the further development of the theory of fractional crystallization, light may be thrown on this difficult problem.

The Pioa rhyolite is transitional into a macroscopically similar rock, very poor in free quartz. In lithological habit and mode of eruption it resembles the trachytes of Papatele and Matafao, suggesting also a similar genetic process. However, Fiji, little more than 1,000 km. distant, bears quartzose, "continental" rocks; one can not absolutely exclude the possibility that the Samoan basalt has here been slightly "contaminated" by silicious crust-rocks forming the edge of the Australasiatic continent. The origin of this rhyolite, almost unique in islands rising from the deeper part of the Pacific, plainly offers another open question.

Chemically and mineralogically all the other rock-types found in the Tutuila composite—the femic Fagasa gabbro and Leone basalt, the trachydoleritic, trachyandesitic, and olivine-free basaltic lavas—match in a general way the requirements of the theory of differentiation from primary basalt. Probably none of them has been formed merely by the subtraction of phenocrystic material from the primary basalt, nor merely by addition of phenocrystic material to primary basalt. The actual process of differentiation was doubtless much more complex, but, obscure as may be the actual details, all the igneous rocks of Tutuila have a family resemblance which seems to find best explanation on the theory just sketched.

Plate B shows a northeast-southwest alignment of the Afono, Pioa, and Papatele masses of the alkalic rocks, as well as elongation of each body in the same direction. Matafao is nearly in the prolongation of the axis of the Vatia body of trachyte. Perhaps, then, the rise of the salic magmas was facilitated by cross-faulting of the island ridge as well as by gas-fluxing. At Matafao, Afono, and Papatele, erosion has destroyed the upper parts of the trachytic bodies, which now have the surface expression of volcanic necks. The Pioa rhyolite is a monolithic crater-filling or a caldera-filling, and may be described as the "head" transitional into a typical "neck," concealed beneath.

The Vatia body of trachyte, including the Pola Island (Cockscomb) mass, is much too elongated to be readily placed in the same category as the other salic bodies. Its differentiation in the form of a vertical, more or less cylindrical column of magma, seems probable, but the final emplacement of the Vatia trachyte involved considerable horizontal flow of this magma. The lateral spreading (Pola or Cockscomb Island) may have taken place along a dike-fissure, or it may have taken the form of a very thick surface flow, located by a valley cut in the older basalts. Since the vertical thickness of the Vatia trachyte is everywhere great, such a flow at the surface must have been highly viscous. The extraordinary viscosity of trachytic flows is well known, so that the second hypothesis is not *a priori* to be excluded. A choice between the two explanations was not compelled by any facts discovered in the field; the writer had no opportunity to land on Pola Island.

EROSION OF TUTUILA.

The map of the island is eloquent of deep erosion by streams and of strong cliffing by the waves of the sea. All the igneous formations touching the sea are cliffed, but two areas have been noted where streams have not yet destroyed constructional forms. One of these is that part of Tutuila which is covered by the Leone basalt and the Leone tuff, with which the tuff cone of Aunuu has been correlated. Little damage has been done to these surfaces, though here and there narrow, shallow gulches have been worn in the hard Leone lava. The other area showing constructional form is the basaltic plateau in the middle of the island, north of Leone. The preservation of this plateau, with a height of about 1,250 feet (380 meters), seems to be due to the unusual massiveness of the volcanic formation, in which relatively few pyroclastic beds weaken the pile of basaltic flows.

For the rest, Tutuila is to be described as a narrow, rugged ridge, with no remnants of the initial volcanic surface; physiographically the island is the oldest in Samoa. The erosion valleys include normal canyon-like forms, broad troughs, and amphitheaters of the type characterizing oceanic islands of basaltic constitution. Though most of the short valleys are doubtless consequent, the higher peaks and ridges, like nearly all the headlands, are composed of specially resistant rocks, either injected masses, monolithic crater-fillings, or heavy lava flows. Stream adjustment has, therefore, begun.

A rough reconstruction, based on the observed dips of the volcanic beds, shows the original pile to have had a maximum height of at least 4,000 feet (1,220 meters) above the present level of the sea. So great has been the denudation that the highest peak, Matafao, measures only 2,141 feet above the same datum; Pioa has a height of 1,717 feet. The likewise resistant trachyte near Vatia culminates in Aoao ridge, at the elevation of 717 feet. The ridge bearing the Alava summit (1,609 feet), on the north side of Pago Pago Bay, is held up by the special strength of a series of thick basaltic flows, free from tuffaceous interbeds (Plate 1, B). Differential strength is illustrated on a smaller scale at many headlands, where hard trap dikes or massive flows have resisted the waves better than the weaker rocks alongside. The weak, capping agglomerate of Tapu Tapu Islet has been long preserved because of the strength of a 20-meter lava flow at the base of the cliffed pyramid.

In spite of some protection by coral reefs, Tutuila and Aunuu are being attacked at many points by the ocean waves. The grandest cliffs, thus kept fresh and steep, are those around Pola Island and on the adjacent mainland. From Leone to Tafuna, the young Leone basalt is continuously cliffed, with the incidental development of scores of fine sea-chasms and spouting-horns. The rock-benches now being widened, along the shore in general, vary in width from a few meters to about 200 meters.

The constructional forms due to deposition include small deltas at the bay-heads, numerous small landslides, many short beaches, and a sand spit at Nuuuli village, on the south shore. The beaches are largely confined to the bays and usually consist of subangular fragments of *Acropora* and other corals, with finer reef detritus. The crests of the storm beaches range from 2 to 3 meters above high tide. Silicious sands, composed of olivine, augite, magnetite, glass, and other volcanic materials, compose the beaches in Leone Bay and in the breached craters at Steps Point.

CHANGES OF LEVEL.

The prolonged denudation of Tutuila was naturally accompanied by the offshore deposition of much sediment. In fact, the chart shows a broad bank or shelf, completely encircling the island and rivaling it in width. (See Plate A.) The total area of the shelf, inside the 100-fathom line, approaches 330 square kilometers, or considerably more than twice the area of the island itself. No known fact is opposed to the conception that the shelf is in part a wave-cut terrace and in larger part a true off-shore bank formed from land detritus, pelagic shells, and interbedded coral débris including old coral reefs. (See sections, Plate B.) The present fringing reefs are seldom as much as 200 meters wide, so that their contribution to the shelf has been very small.

It is difficult to estimate the depth of water on the shelf when it approached completion. If to a great extent it had been crowned with coral reefs, the average depth at that stage may have been only a few meters. If reefs were absent during the growth of the shelf, the depth, a few hundred meters outside the wave-cut belt, should have varied between 20 and about 75 meters, the typical depths for aggraded terraces around reef-free islands. If, on the other hand, the outer part of the original shelf had been built up, in pre-Glacial time, nearly to sea-level by coral growth, and then eroded by the waves of an early glacial stage of the Pleistocene, the surface of the shelf would have been thus lowered some tens of meters below the level of the pre-Glacial ocean and presumably about the same amount below the existing sea-level.

Near the outer edges of the shelf there are extensive shoals which are best explained as old barrier reefs and coral patches, recently drowned. The evidences are twofold; the distribution of the isobaths, and the writer's discovery of coral fragments in the tuffs of the Steps Point craters (Plate B, sections). Chamberlin later found similar fragments in the Aunuu Island cone, which is likewise situated near the outer edge of the shelf. Inshore shoals of roughly similar depths seem to represent contemporaneous reefs of the fringing type; on the north side of the island, barrier and fringe appear to have fused together.

Judging by the analogies of many other shelf-encircled islands, this subsidence may be considered as of the order of 45 to 65 meters (25 to 35 fathoms) in maximum. Inspection of the chart suggests that the western part of the shelf sank 5 to 10 fathoms less than the eastern part, and the northern part perhaps 5 fathoms less than the southern part—the old shelf in effect being slightly tilted toward the southeast.

In view of the various unknown factors, it is possible to assume, with Chamberlin, that the total subsidence has averaged nearly 125 meters (70 fathoms). The present writer's estimate of less than half that amount is based on the fairly direct evidence from the relation of the top of the drowned barrier to present sea-level. The ascertained facts do not seem to warrant a higher estimate except on the assumption that the shelf was covered by coral reefs nearly reaching the water surface and of full thickness (not eroded) at the time when the island began to sink. Until that assumption is made more probable by observations, it seems unsafe to postulate a subsidence greater than 55 to 65 meters (30 to 35 fathoms).

The sinking of the island has already been speculatively explained as an incident in the crustal readjustments connected with the formation of Tonga Deep. A result is the drowning of valleys; hence the bays at Pago Pago (Plate 1, B), Fagaitua, Afono, Vatia, Fagasa, and elsewhere. Dr. Mayor's borings in Pago Pago Bay showed the existence of basaltic lava-flows at such depths under the bay waters that a total subsidence of little more than 55 to 65 meters need be assumed. The hard-rock profile of this bay shows the danger of estimating the amount of subsidence from the curve representing the submarine prolongation of valley sides above sea-level; in the present instance that method would give a maximum depth of the hard-rock profile between 180 and 360 meters (100 and 200 fathoms). In the writer's opinion such extrapolation is likely in general to give too great values for the delevelings registered in the drowned valleys of the tropical islands.

After the drowning, probably after the formation of the Steps Point craters, and certainly after the erection of the Aunuu Island cone, the sea-level stood about 6 meters higher than at present. In that position it remained long enough for the notable erosion of massive lavas on all sides of Tutuila. The resulting cliffs range in height from 10 meters or less to at least 100 meters. The waves could then exert their full force on the island, for, as Mayor discovered, no reefs were then growing on these shores. The evidence is that storm-beaches composed of coral heads and allied detritus are absolutely lacking at the level 6 meters above present high-water level. The present writer examined many bay-heads for information on this point and is quite convinced of the correctness of Mayor's deduction. Storm-beaches made of volcanic-rock materials appear at the higher level, but not a solitary coral head of contemporaneous date could be found.

In 1918 Mayor had recorded low rock-benches on headlands all around Tutuila, with elevations of from 2 to 3 meters above high tide. When these benches were cut, high-water level must have been somewhat higher. At reef-free headlands of Samoa the cliffs are now being driven back by the powerful surf in such a way that the base of each cliff is 2 to 4 or more meters below high-tide level. A similar

relation is common at bold headlands in the North Atlantic, at Saint Helena, Ascension Island, and elsewhere outside the coral-reef belt. From 2 to 4 or more meters must, then, be added to the observed heights of Samoan emerged benches along headlands to get the amount of the shift of sea-level since the benches were cut.

More direct evidence on the amount of the emergence is furnished by the sea-caves cut at the higher level of the sea. One such cave was discovered on the point next east of Faganeanea village, 2 km. west of the entrance to Pago Pago Bay. The cave is apse-shaped, 8 meters high, and 6 meters deep. The floor is covered with blocks fallen from the roof and with bat guano, but the height of the floor was seen to be not less than 4 to 5 meters above high tide. The caves now being cut by the surf elsewhere have floors from 1 to 2 meters below the same level. The Faganeanea cave thus indicates emergence of about 6 meters.

A still clearer instance was found on the headland immediately southwest of Amaua village and a kilometer southwest of Fagaitua village. This is a fine, large cave, with a well-exposed floor standing nearly 5 meters above high-tide level at its outer lip and rising to somewhat more than 6 meters at the back wall. Again the analogy of the modern sea-caves of Tutuila, whose floors at the back walls regularly stand a little above high-tide level, indicates the former high-tide level to have been nearly 6 meters or 20 feet.

The emerged rock-bench is excellently displayed on the eastern shore of Aunuu Island, where the gently inclined facet truncates the tuff beds (Plate 7, A and B). Even now this shore is practically unprotected by coral growth; the waves are therefore rapidly driving back vertical or overhanging cliffs with bases 1 or 2 to 4 meters below high-tide level.

Nearly 100 km. east of Aunuu, Ofu and Tau islands exhibit similar benches with heights sensibly the same as at Tutuila and Aunuu (Plate 8, A). They correspond, too, with the maximum height of the limestone surface of Rose atoll, 140 km. still farther east.[1]

The practical identity of the heights measured for the benches on islands distributed along a line nearly 300 km. long makes it highly improbable that the cause of the emergence is to be sought in crustal upwarping, for this would almost certainly involve differential movement. Correlation of the facts observed in Samoa, with those observed in the Atlantic and with others described in many other parts of the world, has prompted the hypothesis of a world-wide sinking of ocean-level—a eustatic shift. The date of the shift has been assigned, roughly, to an epoch centering around 4,000 years ago. A possible explanation is the change in the world climate which is indicated by fossils in both hemispheres, during post-Glacial time. For details the reader may be referred to the published statements of the hypothesis; there also he will find a note on the importance, in principle, of even this small change of sea-level. [2]

[1] A. G. Mayor, Year Book, Carnegie Inst. Wash., 1920, p. 187; Proc. Amer. Phil. Soc., vol. 60, 1921, p. 62.

[2] R. A. Daly, Proc. Nat. Acad. Sci., vol. 6, 1920, p. 246; Geol. Mag., vol. 57, 1920, p. 247; Amer. Jour. Sci., vol. 1, 1921, p. 391. Since the date of the last-mentioned paper, the writer has found the "20-foot" bench on St. Helena Island, at the Cape of Good Hope, and along the coast of Southwest Africa.

Special search was made for evidence of former submergence to a depth greater than 6 meters above high tide; the results were negative for Tutuila, as well as for all the other Samoan islands visited: Tau, Olosega, Ofu, Aunuu, and Upolu. Friedlaender mapped "elevated coral rock" at Alao and Tula villages, situated in the most easterly embayment of Tutuila. He gives the elevation of the "Lager" of limestone as about 20 meters above sea. The present writer studied both localities, but failed to find any raised limestone except rare coral heads and coral-rock pebbles, evidently carried up from the neighboring storm-beach by the natives.

Some remarks may be added on the relation of these changes of level to the theory of coral reefs in general. A few authors have thought that the writer's Glacial-control theory implies extensive terrace-making around intertropical islands during the Pleistocene period. One reason for this misapprehension is to be found in their failure to note in the preliminary and later statements of the theory clear indications to the contrary, and to realize that the name "Glacial-control theory" is but a *symbol* of a complex hypothesis which includes many principles other than Glacial controls.[1]

This theory, like those of Wharton, Agassiz, Vaughan, and others, is based on the conclusion that most of the living coral reefs began to grow on wide platforms, which had been prepared by prolonged marine action. The widths of the platforms and their approximate accordance in depth below present sea-level imply prolonged stability of the tropical-sea floor during some hundreds of thousands, or a few millions, of years. The duration of the nearly stable condition is, however, no greater than that demanded by the subsidence theory, which, like every other explanation, has to account for the marked flatness of the lagoon floors inside of atoll and barrier reefs. All theories must recognize the necessity of postulating crustal stability in most of the reef-zone of the earth during a considerable part of late Cenozoic time; just as clearly, local deleveling of the crust in that zone must be postulated for earlier geological time, and, in more restricted areas, during late-Tertiary and Pleistocene time. Absolute stability of the crust in the intertropical belt throughout geological time is not an assumption of the Glacial-control theory, and is clearly improbable.

The shelves formed around continents and islands during the period of comparative stability were in large part built up by the accumulation of shore detritus and shallow-water, organic débris. In other part the shelves were developed by wave-abrasion, which was specially effective before reef-building societies of corals were evolved. Even after protective reefs were "invented" by Nature, and before the Glacial period, shelf-building probably continued, outside the fringing reefs; for as yet a widespread development of atoll and barrier reefs overlooking great depths at the outer edges of the shelves was probably impossible.

The pre-Glacial fringing reefs themselves were not wide in absolute measure, since no very wide fringing reef is known in areas that have undergone recent elevation, or elsewhere. Some areas of the intertropical belt might be expected to have

[1] See R. A. Daly, Amer. Jour. Sci., vol. 30, 1910, 304, 305; Proc. Amer. Acad. Arts and Sci., vol. 51, 1915, 174–182, 229–231, 248; Proc. Nat. Acad. Sci., vol. 2, 1916, p. 664; Amer. Jour. Sci., vol. 48, 1919, p. 136.

escaped deleveling since mid-Tertiary time. There the fringing reefs might be expected to have maximum widths; yet no reef of exceptionally great width has yet been mapped. It seems clear, therefore, that, though late-Tertiary fringing reefs did protect many islands from rapid wave-attack, yet the indefinite growth of the reefs outward was prevented. The cause may possibly be sought in the severe conditions of coral life, subject to periodic invasions of sediment which was washed up from the well-graded shelves during exceptional storms.

With the advent of the first glacial stage of the Glacial period, even the slow growth of the reefs was stopped by oceanic chilling and by the increased muddiness of shelf-waters, compelled by the lowering of sea-level. The ocean waves worked first on the soft sands, gravels, and muds of the helves; then on the dead reefs and, finally, on the harder rocks beneath. The earliest glacial stage, like all later glacial stages, was doubtless too short for significant cliffing of the hard rocks, so that pronounced cliffs, then cut, should not now commonly appear above sea-level.

The succeeding interglacial stage is assumed to have witnessed the development of atoll and barrier reefs. As in the case of the living reefs of the two classes, these Pleistocene reefs widened very slowly as they grew outward into deep water.

The waves of the second glacial stage would first destroy these outlying reefs and then continue the planation of the shelves, removing the detrital veneers that had been formed during the interglacial stage; so also with later stages of the Glacial period. Such rhythmic processes continued until the living reefs took root on the shelves, "sandpapered" for the last time in the last glacial stage.

Thus the Glacial-control theory does not demand a general cliffing of the hard rocks of volcanic islands which are now fringed with, or barriered by, coral reefs, though strong sea-cliffs may be expected on islands of the reef-belt, which for any reason have not been protected by reefs for a longer period of time. This theory involves the question whether atolls or barrier reefs have not been developed only since the first deglaciation-stage of the Glacial period. Because the surfaces of coastal shelves are now deeper than in pre-Glacial times, reef corals are now much less exposed to mud-killing by hurricanes. Hence comes the suggestion that reef corals now have specially favorable conditions for rapid growth—conditions never equalled, in general, during pre-Glacial time, though perhaps duplicated during the interglacial stages. However, unfavorable conditions will affect the fringing reefs of the future as soon as the corresponding shelf-profiles have become well graded; for with this grading mud-killing by great storms must become more prevalent.

The facts so far ascertained concerning the structure and topography of Tutuila do not enforce belief in any general explanation of coral reefs. It seems to be necessary to assume subsidence, probably differential, in order to explain the drowned barrier reef. Yet the relation of Samoa to the Tonga Deep means that there may be a quite special occasion for crustal subsidence in this region, a cause not illustrated throughout the atoll-barrier belt of the earth. The drowned barrier reef of Tutuila may have grown up on a normal shelf during an interglacial stage and sunk at some later time. If one may judge from the amount of erosion suffered

by the island, the shelf itself could have been largely built in pre-Glacial times, though somewhat widened during the Glacial period. The shelf is not wide in absolute measure and very long-continued stability of the crust is here not manifest.

The field evidence that reef corals were practically absent from the Tutuila shore before the 6-meter (eustatic) lowering of sea-level represents an important problem not yet solved. If this deleveling is as recent as the late-Neolithic time, the cause of the delay in the colonization by coral larvæ must still be sought. By the Glacial-control theory such delay in the beginning of reef growth is not expected in most of the islands of the coral seas. Hence in order to account for the whole story of Tutuila and its reefs, this theory must be made to include some factor as yet unknown. That the island was long devoid of protecting reefs, in spite of the existence of a shelf, is shown by the great height of the sea-cliffs, cut before the 6-meter shift of ocean-level. The length of that time of active cliff-cutting in hard rocks must have been at least as great as the length of time intervening between the last glacial stage and the late-Neolithic period. This reefless condition of the island may thus conceivably have been continued from the last glacial stage. But the factor leading to the special prolongation of the reefless condition is not easy to discover.

ORIGIN OF PAGO PAGO BAY.

The origin of what is perhaps the most picturesque, as well as safest, large harbor in the Pacific archipelagoes is a problem of special interest. It was first proposed to the writer by Dr. Mayor, who threw out the suggestion that Pago Pago Bay might represent part of a caldera, the western part of which has been filled with younger material, erupted from the Matafao vent (Plate B). At first sight the proof of the comparative youth of the Matafao breccia and trachyte would lend color to this idea; its testing led to a special collection of field data.

The deep weathering of the rocks and the cover of jungle long retarded a definite decision, but the facts finally led to a rejection of the hypothesis. North of the divide between Fagaalu and Fago Togo, and all along the shore between the head of the bay and the harbor entrance, the basaltic flows and pyroclastic interbeds have, in general, southerly dips, at angles from 5° to 30°. They thus have the normal direction of dip for the older volcanics on the south side of Tutuila. North of the bay the dips are regularly to the northward. The conclusion seems to follow that the openings, whence issued the eruptive rocks now found in the area between the bay and the Matafao breccia, are to be located chiefly in the east-west axis of the bay itself. This hypothesis is further supported by the particularly large size of the rock fragments in the breccias around the head of the bay, indicating the close proximity of the explosive vents.

On the other hand, the heavy flows of basalt constituting the bold slope on the north side of the bay are not clearly matched on the south side, where tuffs and agglomerates are much more liberally interbedded. The lack of symmetry on the two sides of the main fissure-zone suggests the possibility of down-faulting or slumping on the south side of that zone, at some stage of the active growth of the volcanic pile. Continued extravasation in the sunken area, followed by strong

erosion, would be later events in the development of the east-west section of Pago Pago Bay.

Further, it is possible that the drainage was initially concentrated in depressions caused by moderate explosions along the axis of the bay. In that way the relatively great size of this drowned valley could be understood, even on the supposition of an almost purely erosional origin. The problem is, then, only partly solved. The safest judgment seems to be that the valley occupied by Pago Pago Bay is essentially an erosional feature, engraved in a structurally complex mass of rocks, including the Matafao breccia. The bay itself is most simply explained as due to the drowning of the valley when Tutuila subsided; a small part of its depth may be due to stream erosion during one or more glacial stages of the Pleistocene, when the base-level was specially low.

GEOLOGICAL HISTORY OF TUTUILA AND AUNUU ISLANDS.

From the alignment of the Samoan Islands and their much more numerous volcanic vents, the ultimate cause of the basaltic eruptions is probably to be traced to a fissure or belt of fissures traversing the suboceanic crust and at least 300 km. in length. The reasonableness of this assumption appears only after an inductive study of the world's volcanic chains, and will not be discussed here. The remarkable degree of parallelism among the volcanic chains of the mid-Pacific suggests a common condition for the development of their respective belts of fissuring. This generalization represents a fundamental problem as yet unsolved. Groll's and other modern maps of the Pacific isobaths show a large number of northwest-southeast wrinkles on the Pacific floor, with amplitudes of from 1,000 to 1,200 or more meters. Are these warps due to stresses set up in the sub-Pacific crust by ancient torsion of the earth? The subsequent adjustments of the crust toward a geoidal figure might be expected to produce local tensions along northwest-southeast lines.

A combination of moderate upwarping and volcanic eruption has possibly been responsible for the initiation of the Samoan and other ridges of the Pacific floor, though the steepness of the upper slopes points to a volcanic origin for the higher part, and the greater part of the volume of each ridge. The oldest exposed lavas of Tutuila are probably as old as the Pliocene; the youngest are clearly Recent.

Eruption of dominantly basaltic lavas is the first actually demonstrated stage in the evolution of Samoa. The oldest visible lavas of Tutuila, however, include not only the primitive basalt but also the interbedded products of its differentiation—mafic basalts, trachydoleritic types, and possibly andesitic basalts. The latter rocks were due to local and temporary changes of magma, and the true basalt has been erupted at intervals, from the beginning of discoverable Samoan history almost to the date of the last eruption. During geologically recent times normal basalt has flowed out at many points in the Manua subgroup as well as in western Samoa.

In Tutuila the long stage of basaltic development was followed by the series of major explosions that produced the Pioa and Matafao breccias. Soon after came the eruptions of the Pioa rhyolite and the Matafao, Papatele, Afono, and Vatia trachytes, which seem to have been erupted contemporaneously or nearly so. These

rock bodies, filling necks and craters and to some extent dike-fissures, opened in the older lavas and breccias, are best regarded as differentiates of primitive basaltic magma. As in Hawaii, the Society Islands, etc., the alkalic types of Samoa are in such volumetric and chemical relations to the basalt that no other hypothesis appears tenable.[1]

The trachytic eruptions took place so long ago that the alkalic bodies and their enveloping rocks have been considerably denuded. During the denudation no volcanic vent appears to have been active in Tutuila. The detritus resulting from the erosion was carried out to sea and built into a broad shelf which completely encircled the volcanic torso. From the magnitude of the erosive work, one must be inclined to date much of it as far back as early Pleistocene, if not Pliocene, time.

When the ocean-level fell, because of the formation of the Pleistocene ice-caps, the Samoan islands, then existing, like most others in the open ocean, probably lost their defense by vigorously growing coral reefs. For a long period the shelf deposits and the weak reef-rocks already formed were subjected to re-gradation by the powerful waves and currents of the Pacific. Thereby the surface of the shelf was lowered, the shelf slightly broadened, and the volcanic part of Tutuila more or less strongly cliffed.

With the return of glacial water to the ocean, the sea-level rose, the temperature and other conditions for reef-growth improved, and an interrupted barrier reef was built near the edge of the shelf. This reef is probably to be assigned to an interglacial stage of the Pleistocene period.

The next important event was subsidence, to the extent of 45 to 65 meters, speculatively related to the deepening of the adjacent Tonga Deep. The movement appears to have been differential, so that the surface of the barrier reef is now not quite level. The old lagoon shows corresponding variations of depth, in spite of gradational processes. In part the drowning of the Tutuila valleys is referred to this subsidence.

After the sinking, eruption was renewed. Perhaps the first result was the formation of a composite cone, just north of Aunuu Island, the relics of which, as west-dipping flows and tuffs, are preserved along the Tutuila shore between Utumea Point and Cape Matatula. However, there is a bare possibility that this cone was formed synchronously with the Aunuu Island cone.

Clearly later than the subsidence was the eruption of the Leone basalt from one or more fissures which roughly paralleled the island axis. The lava flowed over the shelf between Tafuna and the meridian of Leone, and attained such volume as to fill a part of the lagoon where it was about 40 fathoms deep. Soon after the fissure eruption, perhaps within a few days, the two tuff cones at Steps Point and probably also the Aunuu Island cone were built up. The vents at Steps Point passed through old coral reefs, for fairly abundant fragments of corals and other fossiliferous reef limestone occur in the tuffs.[2] These craters are situated just over the area

[1] R. A. Daly, Jour. Geol., vol. 19, 1911, p. 289; *Igneous Rocks and their Origin*, 1914, p. 395 ff. W. Cross, Prof. Paper, No. 88, U. S. Geol. Survey, 1915, p. 87.

[2] No dolomite was found among the fragments, one of which, analyzed by Professor Phillips, gave 97.21 per cent $CaCO_3$ and 1.65 per cent $MgCO_3$ (spec. No. 2640).

where old reef-rock would be expected if a barrier reef had been actually drowned by general subsidence of the island.

At the close of this latest eruptivity, the sea-level stood about 6 meters higher than at present. There it remained long enough for notable marine erosion of pyroclastics and massive lavas on all sides of Tutuila. The resulting cliffs ranged in height from 10 to 100 or more meters and are still largely intact. The waves could exert their full force on the island, because, as first observed by Mayor, there were no reefs then growing on Tutuila. The later, probably eustatic, sinking of sea-level to the extent of about 6 meters, exposed the new rock-benches and sea-caves.

Finally, the conditions again became right for the vigorous growth of corals, and narrow reef fringes and patches have been formed along the shores of Tutuila and Aunuu islands; how far the contemporaneous growth of corals has locally shallowed the water over the drowned barrier, as at Taema Bank, is unknown. The widths of the reefs, interpreted with the known rate of coral growth, are compatible with the conclusion that the eustatic shift of sea-level took place not more than about 4,000 years ago. The living reefs are accordingly ascribed to the latter part of post-Glacial time. The reason for the lateness of the colonization by the corals initiating these reefs remains a mystery. The interruption in reef growth may well be due to chilling and the special muddying of the shore waters during the glacial stage or stages following the inter-Glacial development of the barrier reef; but there seems to have been also some special influence at Tutuila, which prevented the prompt occupation of its shores by corals in the Recent period.

Wave-cutting, the formation of beaches, spits, and landslides, the further widening and deepening of valleys, and coral growth are processes now modifying Tutuila.

OBSERVATIONS ON THE MANUA SUBGROUP OF ISLANDS.

Through the courtesy of the late Governor W. J. Terhune, the writer was enabled to reach Ofu, Olosega, and Tau islands by taking passage on the United States naval tug *Fortune*. A few days were permitted for a reconnaissance of the geology of the three islands; in this work Dr. Mayor gave valued help. Rapid as the examination had to be, some of the results seem worthy of record.

TAU.

Tau is 10.8 km. in length, by 6.8 km. in maximum width (Plate A). Its summit, at 3,056 feet (931 meters), is nearly central. From that point the surface descends northward, eastward, and westward in relatively smooth curves, in principle like those characteristic of Savaii, Hawaii, and other young, exogenous lava domes. The map shows the descent on the south to be precipitous for nearly 350 meters, this cliff running in a course nearly parallel to the shore of the broad bay on the south side of the island. From the foot of that cliff the slope is gentle for the distance of about a kilometer, but there the surface drops precipitously, 450 meters, into the sea. The writer was not privileged to study this slope. Friedlaender states that the two precipices appear to represent the walls of volcanic sinks (Einsturzkratern). His suggestion is of interest as indicating possible homologies with

the great slippings or founderings which seem to have been responsible for the present shapes of Olosega and Ofu islands.

The shore cliffs of northern Tau range from 50 to 150 meters in height. Their bases are now being attacked by the surf, but faulting may have been partly responsible for these cliffs also. If wave-cutting were assumed to be the sole cause, it would be difficult to explain the much feebler development of cliffs at the eastern (windward) end of Tau. On the other hand, the whole island was nipped by the waves when sea-level stood about 6 meters higher than at present. At that time the western shore was benched, with the formation of cliffs 20 to 80 meters high and of rock-benches now standing 2 to 3 meters above high-tide level (Plate 8, A). The correlation of the benches with those of Aunuu and Tutuila has already been noted.

The constructional form of Tau has been very little changed by stream erosion, in spite of rapid gradients. The deepest gorge observed is about 5 meters in depth. Except the cliffs above-mentioned, the chief breaks in the generally smooth profiles are those due to a few low crater-rings at the higher levels. Lateritization of the lavas rarely attains the depth of more than a few centimeters.

Healthy patches of coral occur here and there along the shore, but no continuous fringing reef has been recorded on Tau.

The reconnaissance covered merely the shores and shore-trails of western Tau. All the igneous rocks collected proved to be typical basalts bearing abundant olivine. The flows vary from 5 to 25 or more meters in thickness. Many have ropy surfaces; a few were seen to contain lava tunnels with lava stalactites. Other flows are clinkery, tending toward typical aa or block lava.

Beds of tuff or agglomerate are rare, Tau being essentially the product of successive flows of basalt. However, at the northwest corner of the island, the flows are overlain by two tuff craters, which have been breached by the sea. Each cone has a crater about 600 meters in diameter. The tuffs, in places agglomeratic, are composed of fragments of much altered basalt and of coralliferous limestone; locally, numerous nodules composed of interlocked olivines (90 per cent) pyroxene (6 per cent) and magnetite (4 per cent) were observed.[1]

It may be noted that geological exploration in Tau is now difficult on account of the nearly complete destruction of the forest by the hurricane of 1915. The force of that wind may be appreciated from the reported fact that the sheet-iron roof of a Tau church was carried bodily to Olosega, a distance of about 8 km. Wholesale felling of trees, followed by the speedy growth of jungle in the "down timber" has made travel exceedingly slow and laborious.

OFU AND OLOSEGA.

Ofu and Olosega are twin relics of a single basaltic island which in size was originally comparable with Tau (Plate A). From Nuu islet to the most easterly cliff of Olosega is a distance of 9.2 km. Ofu measures 5.4 by 3.0 km.; Olosega, 4.5

[1] As at the Steps Point cones on Tutuila, the limestone fragments in the Tau tuffs have not been dolomitized. One specimen (No. 2648) gave Professor Phillips 92.28 per cent $CaCO_3$ and 1.06 per cent $MgCO_3$; another (No. 2650) gave 96.68 per cent $CaCO_3$ and 0.82 per cent $MgCO_3$.

by 2.9 km. A tide-way, 200 meters in width, separates them. The maximum heights of Ofu and Olosega are respectively 484 and 639 meters (Plate 8, B).

Each island is strongly cliffed on all sides. Yet more clearly than in the case of Tau, the greater precipices are not essentially the product of wave-cutting. The western slope of Ofu and the eastern slope of Olosega, though somewhat furrowed by stream erosion, largely preserve the constructional profiles of a volcanic cone. The foot of each of these slopes has been benched by the waves, the true sea-cliffs reaching heights of 100 meters or more. The northern and southern slopes give magnificent panoramas of rugged, cliffy slopes, reaching heights of 500 to 600 meters. These are particularly impressive to east and west of the strait between the main islands, where the rocks form a shark's-tooth ridge of fantastic outlines (Plate 9). The whole forms one of the grandest sights in the ocean, recalling the famous Nuuanu Pali near Honolulu.

Three different explanations of these Samoan precipices are conceivable. The curved ground-plan of each set of cliffs suggests an origin in a double evisceration through volcanic explosion, each ragged wall being the emerged part of the rim of a caldera. Or each wall might be considered a fault-scarp, the limit of a sink, analogous to the sinks at Kilauea or Mokuaweoweo in Hawaii. Thirdly, the cliffs might be considered to be the scars left by two gigantic landslips, involving, here again, the bodily or piecemeal foundering of large fractions of the original island.

If the caldera hypothesis were correct, some débris of the great explosions might be expected to appear on the constructional slopes of Ofu and Olosega. This test was applied to the eastern side of Olosega (Plate 9, A). The volcanic rocks were there found to be deeply lateritized, and furrowed by shallow, stream-cut valleys, which themselves have been truncated at the west-facing cliffs. This topographic relation clearly resembles that shown by the truncation of the much deeper valleys of southeastern Oahu at the Honolulu Pali. The shallow runways of eastern Olosega, even within 100 meters of the line of truncation, are locally veneered with large and small, hard, typically water-worn pebbles of basalt. The scattered gravels were obviously rounded by streams which, not long ago, headed far to the westward of the line of truncation, on high ground. One can not avoid the conclusions: that the broad southern embayment embraced by the two islands was very recently occupied by a high conical mass of land; and that the present surface of eastern Olosega is practically identical with that there existing just before the original Ofu-Olosega Island underwent its catastrophic change. On this surface, so well preserved, not a trace of recent explosive débris could be found. The caldera hypothesis is, therefore, extremely improbable, for an explosion on the scale demanded could hardly fail to lodge many rock-fragments on the undamaged surface of the volcano. The freshness of the gravels disproves the idea that the débris of explosion could, since the explosion, have become so weathered as to merge with the prevailing laterite and thus become hard to distinguish.

It is not so easy to decide between the merits of the sink and landslide hypotheses. The former implied some failure of the underpinning, because of deep-seated changes after the original cone was built—a process which has ruled at many

volcanic centers. As Lindgren has suggested, the majestic cliff of Molokai, in the Hawaiian group, was apparently formed in this way. A similar mechanism may have developed the Honolulu Pali, where actual fault-planes (though of small throw) can be observed. Neither in Ofu nor in Olosega was such direct proof of ordinary faulting discovered.

The evidence for or against explanation by landslides is largely buried under the ocean water. Detailed soundings might give the facts enabling a choice between this and the sink hypothesis. Until that choice is warranted, it seems safe to describe Ofu and Olosega as remnants of a single island which has been recently dismembered through partial foundering. The events of 1888 at Bandai-San, Japan, prove that steam explosions may induce or accompany land slipping on a gigantic cale, but the proof of such coöperation in the Samoan case has not been forthcoming. The facts above cited tend rather to exclude explosion as an important factor in the formation of these spectacular cliffs. About two-thirds of the original island has probably sunk out of sight. Whether the cause of the foundering was deep-seated (forming true sinks) or was centered on the special plasticity of out-sloping rock-layers in the body of the original cone (forming landslips) must be left for future investigation. Similar problems are suggested by the topography of Tau, as of many other volcanic masses in the Pacific. An example is seen in the Haleakala "rent" of Maui, interpreted by J. D. Dana as possibly a case of an arrested landslip.[1]

Ofu and Olosega, in contrast with Tau, are principally composed of pyroclastic material—basaltic agglomerates and tuffs. Basaltic flows are irregularly interbedded and, in their turn, dominate at the northwestern end of Ofu and at the southeastern end of Olosega. In the former area, north and south of Aloafao, the basalt is poor in olivine. Elsewhere olivine is generally abundant, in well-formed phenocrysts. High up on the southeastern face of Ofu, a thick flow is composed of coarsely porphyritic olivine-basalt of striking appearance; it forms huge blocks in the talus.

At the shore, directly south of the summit of the razor-back ridge in eastern Ofu is a typical volcanic neck. Elliptical in cross-section, it measures about 25 by 45 meters in horizontal diameters. The neck is constituted of a coarse, massive, olivine-gabbro porphyry which is chemically like the flow just mentioned. The flows and agglomerates traversed by the neck, and probably the porphyry itself, are cut by a dike of olivine-free diabase bearing nodules of basic plagioclase.

The great precipices, especially those on the south side of each island, are riven by a multitude of thin trap or basaltic dikes. These are usually nearly vertical and trend north 60° to 70° east. At the shore, on the east side of the strait between the main islands, the basaltic flows are cut by 20 dikes in a single cross-section only 25 meters long. Dike networks are common in the Olosega cliff, which reminds one strongly of the precipice on Rakata Island of the Krakatoa group. In fact, the slipping or foundering at Ofu and Olosega has given an excellent opportunity to study the internal structure of a typical basaltic cone of the explosive type.

[1] J. D. Dana, *Characteristics of Volcanoes*, 1891, p. 278.

Both Ofu and Olosega are rather deeply lateritized, as well as somewhat dissected by streams, but, because of the more fragmental and porous nature of their rocks as compared with the strong, massive flows of Tau, it is unsafe to conclude that Tau is younger than these other islands.

The brown tuff-cone of Nuu Island is evidently very young. It is being attacked on all sides by the waves, which have cut three Gothic-arch tunnels clear through the islet. The tunnels vary from 70 to 100 meters in length; through them the surges rush with picturesque effect.

BEACH-ROCK IN SAMOA.

In general the beach sands of Samoa, whether calcareous or silicious, are loose and not consolidated. Locally, however, the sands have been more or less firmly cemented, forming "beach-rock." On Tutuila examples may be seen (see Plate A): at the angle of Pago Pago Bay, where the axis of this wide inlet turns westward; opposite Tower Rock and also about 600 meters north of that point; near Amaua; between Alofau and Round Bluff; along the eastern shore of the island; at the entrance to Vatia Bay, western side; in Amanave Bay; and at Leone. Along the southwestern shore of Ofu Island, beach-rock identical in habit with the calcareous beach-rock of Tutuila and with material collected at Tortugas, Florida, was found.

In most cases the Samoan beach-rock is medium to coarse, calcareous sand, cemented with calcium carbonate. At Vatia the detritus is a very coarse conglomerate composed of wave-worn pebbles and trachytic boulders, up to a meter in thickness, mixed with coral débris and shells; the cement again calcareous. The Leone beach-rock consists of an olivine-rich sand, derived from the neighboring ledges of tuff and fresh lava, together with a small percentage of calcareous, detrital fragments; the whole cemented by calcium carbonate.

The lithification has affected the beach materials between high-tide level and a level a few centimeters below that of the low spring tides. At every locality the length of this lithified part of the beach is not more than a few hundred meters, the beach-rock at each end passing rather abruptly into the ordinary, mobile sand or gravel. A similar relation to the loose sand is seen in cross-sections. Each mass of beach-rock is thus a plate of lenticular cross-section, from a meter or less to about 2 meters in maximum thickness; usually from 3 to 10 meters in width; and from 100 to 300 meters in length. The plate dips seaward, at nearly or quite the same angle as the surface of the unconsolidated beach at each end.

The cause of the lithification is an old problem, encountered by geologists working on the shores of the eastern Mediterranean, Brazil, the Florida Keys, and many parts of the tropical Pacific. A few months before visiting Samoa, the writer had been studying the problem, as illustrated at Tortugas, Florida, where Dr. Mayor had indicated its importance and arranged facilities for the study. The mode of cementation at Tortugas was not to be easily discerned, so that the discovery of a sensibly identical type of beach-rock and also a radically different type, in Samoa, was welcomed as giving wider opportunity to test the various published hypotheses of origin.

The nature and amount of the cement naturally claims first attention. Tests with cobalt nitrate, checked by microscopic examination, showed this to be aragonite in all Florida and Samoan samples, including the volcanic-sand rock at Leone. This introduced carbonate occurs in needles that project at high angles to the surfaces of the sand grains, in much the same way as the aragonite tufts in the cavities of the Funafuti coral-rock, described by Cullis.[1] The needles in the beach-rock are invariably very small, ranging from about 0.02 mm. to 0.06 mm. in length. Though the aragonitic deposit in some cases had a ruling thickness of only 0.05 mm., these rocks were well bonded. In no instance could calcite be identified in the cement itself. The amount of the cement varies within the same limits as at Tortugas, where determinations were made in 1919; these will serve also for the Samoan beach-rock.

During the process of measuring the porosity of the Tortugas rock, the specific gravity of the loose beach-sand was also determined. This incidental result may be worthy of statement. Fine-, medium-, and coarse-grained samples were taken at the laboratory wharf, at the north end of Loggerhead Key. They were composed essentially of fragments of coral, shells, and calcareous algæ, without any visible silicious material whatever. The few chitinous grains may be neglected. Five samples gave respective specific gravities (28° C.) of 2.77, 2.83, 2.84, 2.86, and 2.88, with an average of 2.837. Since the specific gravity of calcite is about 2.72 and that of aragonite about 2.94, the sand was seen to contain nearly equal proportions of the two carbonates.

The porosity of the sands from the same locality was found to average nearly 40 per cent.

Three measurements of the porosity of old beach-rock, collected at the light-house dock on the east side of Loggerhead Key, gave 14.7, 14.8, and 16.5 per cent. These values are fairly characteristic of the more thoroughly indurated beach-rock at Tortugas. The porosity of the average beach-rock is higher, and that of the recently (since 1910) and more imperfectly lithified material at the laboratory wharf is of the order of 35 per cent.

With these data, checked by study of thin sections, the cement of the Tortugas rock was found to vary between the limits of 5 per cent and about 30 per cent of the volume of the whole rock. Thin sections showed that lithification is already pronounced when the cement amounts to only 7 per cent of the rock, by volume.

The foregoing figures well serve, in principle, also for a quantitative description of the Samoan beach-rock. Such correspondence in the nature and amount of the cement, the constant relation of beach-rock to tide-levels and beach-slope, the narrow range of thickness for the beach-rock plates, and, as noted below, a constant relation of the plates to offshore shelves exposed to the power of the open ocean, all suggest a common cause for this kind of lithification. That the cementation has not been essentially due to the solution and re-deposition of the detrital material itself is shown in the Leone case, where the detrital grains are olivine, augite, tachylite, and other silicious materials, with a very small percentage of carbonate

[1] C. G. Cullis, Report of the Royal Society Committee on Funafuti, 1904.

grains. Moreover, a comparison of the Floridan and Brazilian beach-rocks proves that the lithification is not a direct function of the amount of detrital carbonate in the sands. The former, composed of practically pure carbonate sands, are no better consolidated than the Brazilian rocks made up of dominant quartz.[1] The Leone rock clearly suggests another source for the carbonate represented in these cements.

A field relation, common to all the Samoan occurrences, is the restriction of the beach-rock to points well exposed to ocean waves and situated to landward of shallow shelves of some width: it was never found along shores protected from heavy wave-action during exceptional storms. The same is true wherever the writer has seen beach-rock along the Florida coast. The remarkable developments on the Bahaman and Brazilian shores seem to be similarly conditioned. Further, Dr. Mayor stated orally that, during his extensive travels in tropical seas, he had never seen beach-rock on other than exposed shores.

Another generalization may be made for the Samoan examples. The formation of beach-rock is there independent of the topography just back of the beach. The lithification has been brought about immediately in front of high, steep cliffs as well as in front of low flats; at points far from any fresh-water stream; and at points close to the mouths of creeks or in front of poorly drained, low ground.

Branner[2] summarized his explanation of the Brazilian beach-rock, thus:

> The hardening of beach sands may be produced in the following ways:
>
> 1. By carbonated rain-water dissolving out the lime carbonate in the upper portions of calcareous sands and depositing it in the lower portions.
>
> 2. By the escape of carbon dioxide from the sea-water when the surf breaks upon the beaches.
>
> 3. By the escape of carbon dioxide from sea-water where it is warmed by the tropical sun.
>
> 4. By the submarine escape of carbon dioxide about volcanic vents.
>
> These processes may have contributed somewhat to the hardening of the Brazilian reefs, but they do not seem competent to account for them altogether. These theories are especially incapable of accounting for the lithification of beaches behind older reefs.
>
> The distribution of the consolidated beaches of northeast Brazil leads to the inference that the consolidation is directly related to the density of the sea-water. The geology and climatic conditions over the adjacent land are, however, important factors in the hardening of the reef sands. It seems probable that the consolidation of the reef sands would not take place if the rainfall were large enough and constant enough to keep the mouths of the streams open and the water of the streams fresh.
>
> In a region of concentrated rainfall and long drouths the river mouths become temporarily closed, and the abundant aquatic and other life in the lagoons thus formed contributed to the organic acids of the waters, which, upon penetrating the wall or dam of beach sand, first dissolves the lime, and then redeposits it when it comes in contact with the dense seawater on the ocean side. In this manner some portions of the beaches have been hardened, while others have remained incoherent.

Branner's hypothesis can not apply at Tortugas, in the Bahamas, or in Samoa, where the climatic and topographic conditions are not of the kinds postulated. The density of the sea-water is of course important, but, since tropical waters seem

[1] J. C. Branner, Bull. Museum Comp. Zool., vol. 44, 1904, p. 175.
[2] J. C. Branner, Bull. Mus. Comp. Zool., vol. 44, 1904, p. 196.

everywhere to be practically saturated with calcium, local lithification is evidently, as Branner remarked, due to a more special control.

In some respects Field's explanation is similar. His brief statement may be quoted in full:

> My theory is that after an exceptionally severe storm, during which fresh sand is swept upon the beach in places and the beach itself scoured in others, the bulk of the key sands above tide-water level are saturated with a strong (rain-water) solution of calcium carbonate. This solution continues to trickle out through the *beach* sands, at ground-water level, for several days and, upon exposure to the air, deposits calcium carbonate in the spaces between the bits of shell, thus forming the "beach rock." The precipitation of the $CaCO_3$ is probably due to the relief of pressure, the escape of CO_2, and the consequent lowering of the solubility of the $CaCO_3$. The fact that the "beach rock" can not owe its origin to the action of putrefying matter in place, such as sea weeds, etc., is, I believe, proved by the total absence of any carbonaceous material in the rock itself.[1]

Field's hypothesis was intended by him to cover the problem only so far as it refers to the Florida beach-rock and its true homologues. However, its application to Tortugas itself raises difficulties. It offers no explanation of the local, sporadic development of beach-rock along the keys. The seepage of rain-water obviously affects the whole of each beach, yet many Florida beaches show no trace of lithification at all, or inclose but quite limited patches of the rock. Like Branner's hypothesis, it does not explain the temporary nature of the conditions leading to the cementation. In Florida, Brazil, and Samoa, new beach-rock is not now being formed at many points, where in fact the beach-rock is in process of destruction by the waves.

It is incredible that the purely calcareous beach-rocks of Florida and of Samoa, in essentials perfectly similar, have been formed by quite different processes. The writer was able to make a direct test of the Field hypothesis, as a conceivable explanation of such rock, at Siufaga village, on the shore of Tau Island. The village lies on a narrow strip of coral sand, fronted by a storm-beach and backed by a low, swampy, heavily vegetated flat. From the rainy, volcanic slopes farther inland, much fresh water enters the swampy belt and percolates through the coral sand. The seepage is so rapid that the sea-water is kept largely excluded from the interstices of the storm-beach. Hence the natives are able to get potable water at low tide, by scooping out holes in the sand just in front of the lapping waves and nearly a half meter below mean-tide level. The conditions specified by Field's hypothesis seem, thus, to be here ideally met; yet there is no lithification of this beach. The case at Siufaga also shows that Branner's hypothesis can not be valid there.

Field's explanation can not, of course, apply in the case of the olivine sand at Leone; nor will it do to assume a different cause of lithification, for the aragonitic cement of the Leone rock and the general field relations are too similar to the beach-rock at Tortugas. As Branner concluded, the topographic and climatic conditions of the Brazilian coast are not favorable to the explanation of the famous stone reefs by the seepage of rain-water falling on the corresponding beaches.

[1] R. M. Field, Carnegie Inst. Wash., Year Book No. 18, 1919, p. 198.

A different line of thought was suggested to the writer by the fact first observed by Dr. Mayor and his associates at the Tortugas laboratory. The destructive hurricane of 1910 piled a large amount of calcareous sand on the site of the laboratory wharf. Much of this sand seems to have been torn out of the broad shelf offshore. Less than two years afterwards, the sand between tide-marks had already become lithified to a depth reaching a maximum of about 75 cm., resulting in an elongated lense of typical beach-rock. The cementation took place under the cover of 25 to 100 cm. of sand, which was not lithified. By 1919 the cover was largely removed and much of the beach-rock itself was already cut away by the surf.

This sequence of events has led to the inquiry whether beach-rock in general owes its origin to the sudden driving of shelf sands on to the shore by major storms. The observed relations of beach-rock plates to shelves and the open ocean, as above described, agree with this suggestion. Some of the Samoan plates are situated at the inner edges of reef flats which are significantly covered with negro-heads in special abundance; the latter demonstrating former wave-action of extraordinary violence. If such facts from the field be assumed to show that hurricane control has been important, one is naturally led to consider what special property of shelf sand might initiate the lithification.

Ordinary beach sands are comparatively free from organic material other than clean fragments of shells and skeletons. On the other hand, shelf sands in the tropics are charged with considerable amounts of decaying animal and vegetal matter and with living bodies. To get some idea of the amount of carbonaceous material in the sand of the Tortugas shelf, a large sample was secured, with the use of a diving helmet, about 100 meters from the laboratory wharf, at a depth of about 2.5 meters. While digging up the bottom sample, some of each shovelful (perhaps one-fifth) was lost. The rest was fractioned and treated with caustic alkali; the soluble, organic material was found to be roughly 5 per cent of the sample by weight.

The shelf sand cast on the shore by a hurricane is, then, likely to be specially "dirty." Bacterial decomposition of this organic matter must tend to cause a precipitation of calcium carbonate from the sea-water which slowly creeps through the sand because of tidal and other changes of level. Incipient cementation of the sand may be postulated as a reasonable consequence.

However, bacterial action does not seem competent to explain all of the cement in average beach-rock, making up 10 to 30 per cent of the whole volume. It is practically certain that the original mass banked up by a great storm would not contain enough decomposable organic matter. On the other hand, the bacterial decay is conceived to be important as a fixing agent; the initial cement, so developed, suffices to prevent differential movements among the sand grains until other, quantitatively more potent, causes of precipitation have had time to do their work.

Several chemists have shown that tropical sea-water is saturated with calcium carbonate under ordinary surface conditions. Is it not possible that the new, clean carbonate, formed by putrefaction, may act as a nucleating agent and cause further precipitation of the cement? Two other conditions for supersaturation are more

obviously to be considered. At low tide the sand and inclosed sea-water are heated by the sun's rays, carbon dioxide escapes, and calcium carbonate must be thrown out of the sea-water solution. Secondly, the sea-water of the breakers and the water moving slowly through the beach sand are mixed with air. Under the varying pressures produced by the waves, air is forced through the interstitial water. As Johnston and Williamson point out, such aeration should lead to supersaturation.[1] The precipitation resulting from the two causes is practically confined to the thin layer of the banked-up sand, lying between high-tide level and a level a little below low-tide mark—exactly the position where beach-rock occurs. So long as the initially cemented sand keeps its proper relation to the breakers, and is, for example, not too deeply covered with imported sand, the cement can thicken and grow more resistant to blows; until the original interstices have become more or less completely filled. On the other hand, the conditions of shore erosion may lead to the destruction of the new bank before a strong rock could be formed.

This hypothesis seems to explain the characteristic lithological features of beach-rock; its sporadic appearance on tropical beaches; its relations to wave-belt and tides; its limited thickness; and the seaward dip of the plates or lenses of beach-rock. That ordinary, clean sands are not cemented is explained by their incessant or periodic movement through wave-action, and by the lack of any special cause for bonding, preliminary to the more important cementation through the aeration and heating of the sea-water. Field's objection, that, on the hypothesis just outlined, there should be a notable proportion of decomposable organic matter in a given sample of beach-rock, whereas he finds it to be absent, is not well taken; for the actual cleanness of the beach-rock is just what would be expected if bacterial decomposition had been thorough.

The offered explanation evidently needs checking by experiment. In May, 1919, with the help of the staff of the Marine Laboratory at Tortugas, a large cask was filled with shelf detritus, dug up at a point offshore from the laboratory. The sides and ends of the cask were perforated, to permit of the easy flow of sea-water through the mass, and the whole was buried at the proper depth in the beach. It was hoped that, after a year or two, the cask might be opened, with the object of seeing whether its contents had become in any degree cemented together. Unfortunately, the hurricane of September, 1919, tore up the cask and carried it several hundred meters along the key. There left exposed to the air, this material can not be used as a test. The experiment should be duplicated. On the other hand, this hurricane itself improved upon an artificial experiment. Like that of 1910, it threw up on the beach a large quantity of shelf-sand, which, a year afterwards, was found by Dr. Mayor to have been hardened into beach-rock.

[1] J. Johnston and E. D. Williamson, Jour. Geol., vol. 24, 1916, p. 739.

SUMMARY.

The principal conclusions of this paper may be thus summarized:

1. Of the Samoan chain of volcanoes Tutuila and the Manua subgroup of islands have been studied. Tau, Ofu, and Olosega are essentially basaltic throughout. In Tutuila, an exogenous lava-dome, basalt dominates, but its differentiates—trachydoleritic basalt, trachydolerite, trachyandesite, limburgite, highly mafic olivine-gabbro, alkalic trachyte and alkalic quartz-trachyte (rhyolite)—are also represented. The more alkalic bodies have the forms and structural relations of volcanic necks, endogenous domes or crater-fillings, and dikes, which cut the dominant basaltic flows.

2. In chemical composition the average basalt of Tutuila is almost identical with the average basalt of Hawaii and approximates to the average plateau basalt of the world.

3. The alkalic trachytes, trachyandesite, and trachydolerite of Tutuila are regarded as differentiates of ordinary basalt, a magmatic type common to both of the so-called "Pacific" and "Atlantic" suites. Once again the division of igneous rocks into "Pacific" and "Atlantic" suites is seen not to be supported by either geographical or chemical relations.

4. The cause of the differentiation of alkalic trachyte from basalt represents an unsolved problem. The influence of volatile matter—water or carbon dioxide or both—in special abundance may be an important control in the process, but actual proof of this has not been forthcoming. The origin of the abundant pyroxene andesites elsewhere is a closely related question.

5. At least in part the Pioa dome of Tutuila is a quartz-bearing trachyte, approaching a true rhyolite. The quartz is micropoikilitic and identical in habit with the quartz of closely similar quartz-trachytes of Ascension Island and of East Africa. The Pioa rock exemplifies the very rare cases where free, "primary" quartz has been found in lavas of the open-Pacific region, and is perhaps farther removed from visible terranes of "continental" rocks than any other lava bearing primary quartz hitherto recorded in the Pacific. The question is raised whether the edge of Australasia really extends as far east as Samoa.

6. A possible explanation of the common eruptive sequence—basalt, trachyte, basalt—at volcanic centers is proposed.

7. Three new examples of rapid change of color of igneous rocks, when exposed to the air, are described.

8. At the surface of each layer the tuffs of Tutuila were hardened immediately after deposition. This lithification is another problem awaiting solution.

9. Physiographically speaking, Tutuila is the oldest of the Samoan islands. Its oldest supermarine lavas are no younger than an early stage of the Pleistocene period and may be Pliocene, if not older. The youngest eruptives are quite recent. From their degree of dissection the Manua group of islands may be assumed to date from late-Pleistocene or Recent times.

10. Tutuila has subsided some tens of meters. Its sinking seems to have been connected with the formation of the adjacent Tonga-Kermadec Deep.

11. After that subsidence the shores of Tutuila, the Manua group of islands, and Rose atoll have emerged about 6 meters. The emergence appears to be due to a world-wide sinking of sea-level, not more than 4,000 years ago.

12. Before the 6-meter emergence Tutuila was not defended by coral reefs, as Mayor discovered. The cause of their absence is not understood, though it may be associated with the conditions of the last glacial stage of the Pleistocene period.

13. The facts observed in Samoa are consistent with the writer's Glacial-control theory of the living coral reefs, but these islands do not offer definite criteria for any general explanation of the reefs. Emphasis is once more laid on the reasonableness of assuming that atolls and barrier reefs were very rare or even non-existent before the first glacial stage of the Pleistocene period, and that the platforms now crowned with atolls and barrier reefs are shelves and banks, largely detrital, formed during pre-Glacial time because of the absence of reefs other than those of the fringing class. A cause of the narrowness of all pre-Glacial (fringing) reefs is suggested.

14. The remarkable topography of the twin islands, Ofu and Olosega, finds satisfactory explanation in a double foundering. Until the submarine relief is determined by soundings, it does not seem possible to decide whether the foundering was due to ordinary faulting or to landsliding on a grand scale.

15. The origin of beach-rock is discussed in the light of field and laboratory studies at Tutuila, at the Manua group of islands, and at Tortugas, Florida. Preference is given to the view that the formation of beach-rock is controlled by the action of major storms, which quickly pile up shelf-sediments along the littoral. In their new position these sediments are liable to rapid lithification and are thus unlike beach sands of the usual type.

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Plate 2.—A. Sea-cliffs and sea-stacks cut from the Leone lava, dipping seaward at a low angle. Photograph by Mayor.

B. Matafao Peak with Leone lava in foreground; Pioa in right background. Photograph by Mayor.

Plate 3.—A. Fallen block of Pioa quartz-trachyte, in front of fallen block of massive Pioa breccia (basaltic). The trachyte shows the characteristic pitted surface of weathering and the common contorted, fluidal banding. Hammer 70 cm. long. Shore at Aua Village.

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B. Fresh Vatia trachyte, dark gray-green in color.

C. Whitish-gray Pioa quartz trachyte; specimen essentially identical in field habit with the most abundant phase of weathered Vatia trachyte.

Plate 5.—A. Detail of stratification characteristic of Leone tuff; at shore about 1.5 kilometers south of Leone.

B. Ropy surface of young Leone lava-flow. Photograph by Mayor.

Plate 6.—A. Bedded tuff at rim of crater, east side of Aunuu Island. The beds on the left dip seaward, centrifugally with respect to the crater; they are in unconformable contact with centripetally dipping tuff (on the right), which fell into the crater during the last explosions. Blocks of basalt in this younger part of the tuff. Photograph by Mayor.

B. Emerged wave-cut bench in centripetally dipping tuffs, east side of Aunuu Island; bench 2 to 3 meters above high tide. Crater rim in background; center of crater to right of picture. Photograph by Mayor.

Plate 7.—A. Emerged sea-bench cut in tuffs, east side of Aunuu Island. The bench is 2 to 3 meters above high tide. In the high cliff the centrifugally dipping beds of tuff are seen; on the right these are unconformably overlain by centripetally dipping beds. Photograph by Mayor.

B. Surface of emerged sea-bench cut in tuffs, east side of Aunuu Island; height of bench the same as that shown in A. Photograph by Mayor.

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B. Olosega and Ofu Islands, seen from Tau Island at a point about 8 kilometers from Olosega. The slope of Olosega on the left has been determined by the great subsidence which caused the disappearance of the southern part of the original Ofu-Olosega Island. Photograph by Mayor.

Plate 9.—A. Ofu (left) and Olosega (middle background) islands, seen from a ship, looking east-northeast. The water in the middle of the view overlies one area of the sunken part of the original Ofu-Olosega Island. Photograph by Mayor.

B. Ofu Island from the strait between Ofu and Olosega Islands. The steep slopes on each side of the ridge seem to be due to slips or faults. Photograph by Mayor.

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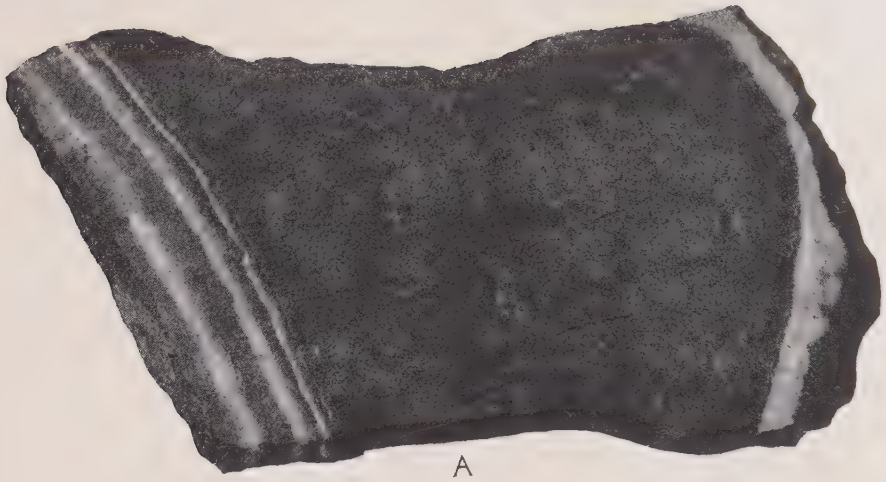

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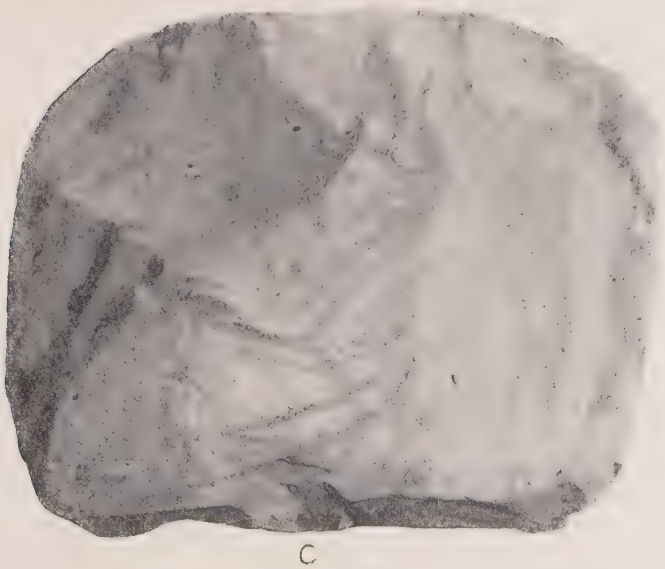

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THE GEOLOGICAL INTERPRETATION OF THE CORAL REEFS OF TUTUILA, AMERICAN SAMOA.

By

Rollin T. Chamberlin.

With seven plates and five text figures.

[Note.—The manuscript of this paper was submitted by the author to Dr. Mayor, former Director of the Department of Marine Biology of the Carnegie Institution of Washington, on April 13, 1921.]

THE GEOLOGICAL INTERPRETATION OF THE CORAL REEFS OF TUTUILA, AMERICAN SAMOA.

By Rollin T. Chamberlin.

INTRODUCTION.

The Samoan or Navigators' Islands are a volcanic group located in the South Pacific between latitudes 13° 30′ and 14° 20′ south and longitudes 168° and 173° west. They are truly oceanic, having been built from the great depths of the Pacific through the accumulation of large masses of eruptive material. Politically the group is divided by the one hundred and seventy-first meridian into British Samoa to the west and American Samoa to the east. Savaii and Upolu, the two largest islands, belong to British Samoa, now a dependency of New Zealand. American Samoa comprises the islands of Tutuila, Aunuu, Tau, Ofu, Olosega, and Rose Atoll. Of these, Tutuila is the largest and most important.

Tutuila is a slender island of irregular outline, whose longest dimension lies nearly due east and west. Its length is 19.6 miles, exclusive of some small offshore remnants of its former self. The greatest width, measured from Steps Point on the south side to the end of the promontory just west of the village of Asu on the north shore, is 5.8 miles, but the average width is barely 3 miles.

While there are no really high mountain peaks on Tutuila, the island is nevertheless extremely rugged in contour. Nearly everywhere the slopes rise steeply from the shore, and in many places stand as abrupt cliffs several hundred feet in height. The culminating point is the picturesque pyramidal peak of Matafao, which attains an elevation of 2,141 feet. Another prominent peak is Pioa, 1,717 feet, sharply sculptured and beautiful in its bold outlines. More than a dozen other peaks rise over 1,000 feet above the sea. With only one or two exceptions these, in consequence of the narrowness of the island, stand as sentinels along the tortuous backbone ridge. From the narrow, sharp-crested divide, deep ravines and short, steep-sided valleys descend quickly to the sea. Waterfalls abound. While some of the streams enter the ocean without notable embayments, most of them empty into distinct bays which indent the high, rock-bound coast at many points.

The most conspicuous of these is Pago Pago Bay, which affords one of the finest harbors of the globe and has become the site of the United States Naval Station. This splendid bay, 3 miles in length, has advanced so far into the land that it almost cuts the island in twain. Its entrance is to the southward, but its head is now actually within less than 0.75 mile of the north shore of the island, though separated from it by the sharpened divide whose lowest col is more than 600 feet above tidewater. The numerous bays and coves indenting the coast have made the present shore-line extremely irregular.

This volcanic island has been built up from the floor of the deep sea by the repeated outpouring of lavas, largely basaltic, together with frequent outbursts of pyroclastic material of varying degrees of coarseness. Structurally, Tutuila is thus a succession of lava-flows of varying thickness, interspersed with beds of volcanic tuff, agglomerate, and breccia. These have been invaded by scattered dikes and by some very conspicuous larger masses of trachyte. As a general rule, the separate flows and pyroclastic beds dip gently toward the sea and away from the higher parts of the island. Along the shores the average angle of dip is about 14°, though in some places the oceanward slant of these structures is as much as 30°, or even 35°. The changes in the direction of dip from point to point show that the flows have radiated from various volcanic foci in different parts of the island.

But to-day most of the ancient craters which contributed to the building of the island are no longer immediately apparent, for the island is old and very extensive denudation has greatly modified its aspect. The constructional slopes of volcanic accumulation have given place to degradational slopes, and the original volcanic topography has largely disappeared. With the advance of the stream-erosion cycle, the island has been brought lower and lower, while the never-ceasing waves have cut back its shores farther and farther. The present island is but a skeleton of its former self, much reduced in altitude and covering less than half of its original area.

Tutuila is surrounded on all sides by a broad submarine shelf, which has an average width of approximately 2.5 miles (see Plate A). The greater portion of this shelf is submerged less than 50 fathoms, but a few of the deeper portions reach depths of more than 60 fathoms. Perched on this platform, nearly a mile from the mainland of Tutuila, is the smaller island of Aunuu. This is a comparatively recent tuff cone which still preserves a well-defined crater and crater lake. This broad, fringing shelf is also the locus of the coral activities whose critical investigation was the prime object of the expedition to Samoa.

THEORIES OF CORAL REEFS.

The origin of coral reefs has long been a debated question and the literature of the subject has consequently become enormous. This, however, is not the place to review in any detail the development of coral-reef theories; that has been done recently by Davis,[1] Daly,[2] Vaughan,[3] Mayor,[4] and others. The problem before us, rather, is to consider the leading theories of coral-reef formation in the light of the studies carried on in Tutuila.

Coral reefs are of three sorts: (1) Fringing reefs, built along the shores where the coral polyps first gained foothold; (2) barrier reefs, separated from the shores by lagoons of varying depth; and (3) atolls, ring-like reefs inclosing lagoons above which no land of any consequence appears. Fringing reefs, because of their relative

[1] W. M. Davis, *The home study of corals*, Amer. Geog. Soc. Bull., vol. 46 (1914), pp. 561–577, 641–654, 721–739.

[2] R. A. Daly, *The glacial-control theory of coral reefs*, Amer. Acad. Arts and Sci., vol. 51 (1915), pp. 157–251.

[3] T. W. Vaughan, *Contributions to the geology and paleontology of the Canal Zone*, U. S. Nat. Mus. Bull. 103 (1919), pp. 241–246 and 325–329.

[4] A. G. Mayor, *Ecology of the Murray Island coral reef.* Papers from Department of Marine Biology, Carnegie Inst. Wash., vol. IX. (1918), pp. 1–48.

simplicity, have occasioned the least difference of opinion. The real contention has been over the origin of barrier reefs and atolls, and it has been largely for the elucidation of their origin that various theories have been advanced. Let us consider first the essentials of the different hypotheses and the special contentions of each.

THEORY OF SUBSIDENCE.

The time-honored explanation of barrier reefs and atolls has been the familiar theory of subsidence originally developed by Charles Darwin,[1] afterwards extended by J. D. Dana,[2] and recently elaborated by W. M. Davis.[3] According to this theory in its typical form, corals attaching themselves to volcanic islands in the tropical seas first develop fringing reefs along the shores. With the passage of time, the volcanic pile slowly sinks, but as it sinks the upward growth of coral keeps pace with the subsidence, so that the growing coral-heads maintain themselves near sea-level. The coral growth is more rapid on the outer side of the reef than on the inner side, where the restraining influence of land-derived sediment is most felt. The result is that as the volcanic mass sinks and the corals build upward, the fringing reef becomes a barrier, separated from the shore by a lagoon (fig. 1). Waves attack the exposed portion of the reef and the detritus is washed down the outer slope, enlarging the base of the coralline mass and developing a coral talus slope. If the volcano continues to sink until the central land-mass finally disappears beneath the waves, the barrier reef becomes an atoll (fig. 2).

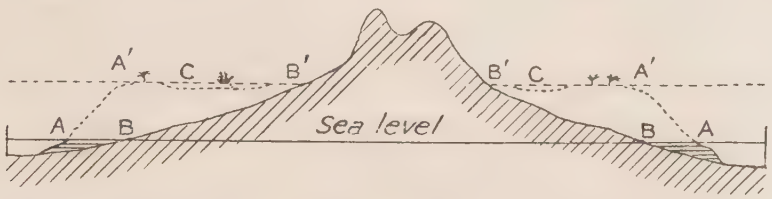

FIG. 1.—Darwin's diagram to illustrate conversion of a fringing reef into a barrier reef.
AA, Outer edge of the reef at level of sea.
BB, Shores of the island.
A'A', Outer edge of the reef, after its upward growth during a period of subsidence. The cocoanut trees indicate coral-islets formed on the reef.
CC, The lagoon-channel between the reef and the shores of the now-encircled land. Ship sailing on lagoon.
B'B', The shores of the encircled island.

Every hypothesis has its own essential features and peculiar characteristics, which distinguish it from other hypotheses. The Darwinian hypothesis in the form most strongly urged would be distinguished among other things by three peculiarities:[4]

(1) The reef in each case has been built upon a sloping surface.

[1] Charles Darwin, Coral reefs (1842).
[2] J. D. Dana, *On coral reefs and islands* (1853); *Coral reefs and coral islands* (1872).
[3] W. M. Davis, *Dana's confirmation of Darwin's theory of coral reefs*, Amer. Jour. Sci., vol. 35 (1913), pp. 173–188. Supplemented by several more recent papers.
[4] Darwin recognized the possibility that corals by growing on the margin of a slightly submerged platform (however formed) might produce a barrier reef or an atoll directly, but he practically dismissed this possibility as very exceptional and of little consequence.

(2) To build up some of the broader submarine banks from the slopes of an average volcanic island would necessitate the accumulation of a vast amount of coralline material.

(3) If the original island has not been completely submerged, shore phenomena indicative of subsidence should be in evidence.

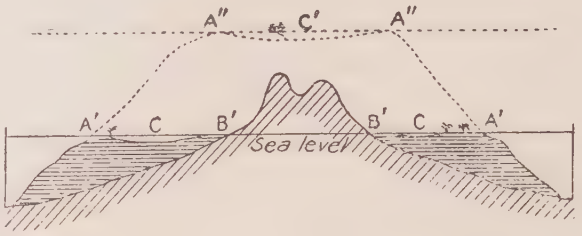

FIG. 2.—Darwin's diagram to illustrate conversion of a barrier reef into an atoll.
A′A′, Outer edges of barrier reef at level of sea.
CC, The lagoon channel.
B′B′, The shores of the island, generally formed of low alluvial land and of coral detritus from lagoon-channel.
A″A″, The outer edges of reef, now forming an atoll.
C′, The lagoon of the newly-formed atoll. According to scale, the depth of the lagoon and of the lagoon-channel is exaggerated.

THEORY OF SOLUTION.

Various investigators, impressed with the fact that under some conditions coral limestone is a comparatively soluble rock, have favored the hypothesis that barrier reefs have developed from fringing reefs by solution of the limestone on the shoreward side of the reefs, where coral growth has practically ceased. They believe that in this way a lagoon is produced, while the reef is maintained by vigorous growth on the seaward margin. Though the idea that atolls could be produced by solution of the inner portion of a limestone mass was put forward by Carl Semper[1] as far back as 1863, the solution theory has come to be more closely associated with the name of Sir John Murray,[2] who further elaborated the possibilities of this principle, and became one of its most prominent advocates. The theory of solution was also strongly supported by Alexander Agassiz,[3] who visited nearly all of the atoll groups on the globe.

Barrier reefs and atolls would thus be explained without calling for subsidence. According to Murray, they would develop alike in areas of slow elevation, of rest, or of slow subsidence. But the theory is absolutely dependent upon the ability of sea-water to dissolve calcium carbonate under the conditions existing in tropical seas. This affords a means of testing its validity.

THEORIES OF PLANATION.

In the third group are the theories of marine planation whose prime postulate is an antecedent wave-cut platform upon which the corals have built their structures. The underlying idea is not a new one, for it was expressed in unmistakable form by Tyerman and Bennett in their diary while visiting the Society Islands in 1821.[4] Guppy in 1890 clearly stated his belief that barrier reefs have developed

[1] Carl Semper, *Reisebericht*, Zeitsch. für wiss. Zoologie, Bd. 13 (1863), pp. 563–569.

[2] Sir John Murray, *On the structure and origin of coral reefs and islands*, Proc. Roy. Soc. Edinburgh, vol. 10 (1879–80), pp. 505–518.

[3] Alexander Agassiz, *The coral reefs of the tropical Pacific*, Mem. Mus. Comp. Zoology, vol. 27 (1903).

[4] Daniel Tyerman and George Bennett, *Journal of voyages and travels*, Compiled by James Montgomery, First Amer. Ed. vol. 1 (1832), pp. 158–159.

on the outer portions of submarine platforms cut by the action of the sea.[1] Admiral Sir W. J. L. Wharton, noting the flatness of the floors and uniformity of depth in atoll lagoons, came to the conclusion that these features have resulted from marine planation.[2] He suggested that a volcanic island might be worn down by marine agencies to a depth of 30 fathoms or more, thereby producing a submarine bank on which up-growing corals could form an atoll, and he definitely put forward the view that while other factors, such as moderate subsidence, etc., may have entered into the final result, "the cutting down of volcanic islands by wave-action and currents has had a greater share in providing suitable bases for coral atolls than any other process of nature."

Various different lines of evidence have led other investigators to similar conclusions. Alexander Agassiz, in addition to advocating the potency of solution, also reintroduced in his reports the idea of wide sea-cut platforms on the borders of volcanic islands and the growth of a comparatively thin veneer of coral on the outer edges of such platforms, thus producing, as Davis has noted, barrier reefs without subsidence, elevation, or solution.[3] In similar fashion, the formation of the extensive, but almost flat plateau, from which the atolls of the Maldive group rise, was attributed by Stanley Gardner to submarine planation.[4] As this plateau now lies beneath about 160 fathoms of water and is characterized by a hard bottom, he reasoned that it is current-swept at the present time and that submarine planation is effective to depths as great as this. In more recent times the incisive work of Vaughan in the Antillean region has added much evidence in favor of the hypothesis of planation.[5]

In 1902, E. C. Andrews showed that the foundation on which the Great Barrier Reef of Australia rests does not come to an end with the southern limit of the coralline mass, but continues southward as a submerged platform into the cooler seas, from which he inferred that only a part of the whole structure is formed of coral growth.[6] The coral reefs are perched upon a flat shelf resulting apparently from marine planation in part, and in part from the submergence of a coastal plain. W. G. Foye states that in the Fiji group barrier reefs are now developing on platforms of elevated limestone which have been eroded to fairly even surfaces by atmospheric solution and later submerged.[7]

In general, the modern barrier reefs of Fiji occur where coastal-plain tracts have been submerged, either due to tilting or faulting. Finally, as the result of these studies, and of his own very extensive coral investigations, Vaughan has come to the general conclusion that offshore coral reefs form on antecedent flattish basements during and after submergence in areas where the general ecological

[1] H. B. Guppy, *The origin of coral reefs*, Victoria Inst. Jour. Trans., vol. 23 (1890), p. 61.

[2] Sir W. J. L. Wharton, *Foundations of coral atolls*, Nature, vol. 55 (1897), pp. 390–393.

[3] Cited by W. M. Davis, *Dana's confirmation of Darwin's theory of coral reefs*, Amer. Jour. Sci., vol. 35 (1913), p. 174.

[4] J. Stanley Gardner, *The formation of the Maldives*, Geographical Jour., vol. XIX (1902), p. 288.

[5] T. W. Vaughan, *op. cit.*, pp. 238–332; *Corals and the formation of coral reefs*, Smiths. Ann. Rept. for 1917, pp. 189–276 and other papers.

[6] E. C. Andrews, *Preliminary note on the geology of the Queensland coast with reference to the geography of the Queensland and New South Wales plateau*, Proc. Linnean Soc., N. S. W., Pt. 2 (1902), pp. 146–185.

[7] W. G. Foye, *The geology of the Fiji Islands*, Proc. Nat. Acad. Sci., vol. 3 (1917), pp. 305–310.

conditions are suitable for coral growth.[1] This more general view thus lays its stress upon pre-existing platforms and appropriate ecological conditions, whether the flattish areas have been produced by marine planation or have developed in other ways.

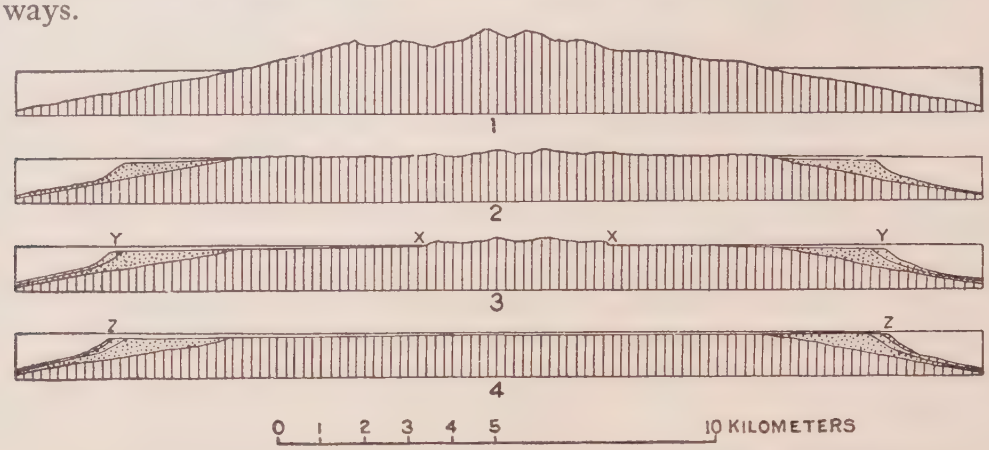

FIG. 3.—Daly's sections to illustrate the development of barrier reefs and atolls according to the Glacial-control theory.

Section 1. A normal volcanic island.

Section 2. The same island largely peneplained, with the necessary formation of an encircling embankment of detritus (stippled).

Section 3. The same island, extensively benched by waves, involving some increase of embankment. Such benching is expected in very old islands which have been exposed to active abrasion, either because of the Pleistocene chilling of the ocean or because of temporary failure of reef protection in pre-Glacial time.

Section 4. Complete truncation of the same island by continued marine abrasion, with a slight broadening of the embankment. This is a stage that, in many instances, was possibly attained in pre-Glacial periods as well as during the Pleistocene.

In Sections 2, 3, and 4 the size of the embankment, as drawn, corresponds merely to the bulk of purely inorganic detritus. If intermixed reef and other organic material were allowed for, the embankment must be represented as broader. After the abrasion, the fringing, barrier, and atoll reefs would be favorably located at X, Y, Z, respectively. Shifts of sea-level are not shown.

The sections are drawn to scale and are also intended to show the great areal extent of the weak embankment materials, laid down around old oceanic volcanoes in pre-Glacial time. About half of the platform represented in section 4 is underlain by these materials, which must have offered little resistance to the benching surf of the Pleistocene period.

GLACIAL-CONTROL THEORY.

A special type of marine planation hypothesis has been called by Daly the glacial-control theory. According to it, the coral reefs have been built upon wave-formed platforms developed, in part at least, at times of lowered sea-level during the stages of maximum glaciation (fig. 3). It has long been recognized that the abstraction of water from the sea to form the extensive glaciers of the Pleistocene glacial epochs necessitated, in consequence, a certain lowering of sea-level. With the amelioration of climate and the melting of the ice-caps, this water would be returned to the ocean, restoring the level. As far back as 1868, Alfred Tylor suggested that the upper 600 feet of coral deposits in the Pacific Ocean might be explained as well by oscillation in the sea-level due to the ice-caps of the glacial

[1] T. W. Vaughan, U. S. Nat. Mus. Bull. 103 (1919), p. 329.

period as by the accepted hypothesis of sea-bottom subsidence.[1] Dana had stated that the deepening of the ocean bed from which the coral islands rise must have amounted to at least 3,000 feet.[2] Two years later Thomas Belt estimated that the lowering of glacial sea-level, on the assumption that the ice was equal in the two hemispheres at the same time, could not have been less than 2,000 feet, and may have been much more. This led him to consider the alternative hypothesis that the phenomena connected with the growth of coral islands, which were then ascribed to a gradual sinking of the ocean floor, might perhaps have been produced equally well by the return of the sea to the level at which it stood before the glacial period.[3] Upham, accepting the estimate that the coral islands indicated a shifting of strand-line of perhaps 3,000 feet, also attempted to match this figure with the drop resulting from the removal of water during glaciation.[4]

In 1882, Penck made an estimate of the amount of lowering of sea-level to be expected in consequence of withdrawal of water to form the Pleistocene ice-caps, but later, in considering the effects which shifting oceanic level would have upon the building of coral reefs,[5] he preferred to use Drygalski's figure of 150 meters.[6] But as none of these investigators followed up their suggestions with further work, or made any serious attempts to test out the validity of the hypothesis, it has remained for Daly to work it out in full detail and to become its chief exponent.[7] He has stated the argument as follows:[8]

The available data seem to show that the whole of the ocean was chilled during the Pleistocene glacial period. Over wide stretches of the tropical seas the reef corals were exterminated or greatly weakened in their reef-building power. The land-masses or shoals, which had been defended by the pre-Glacial living reefs in those regions, were now successfully attacked by the waves of the open ocean, and benched. At the climax of glaciation, the waves of the tropical seas ran over a surface lower than now: first, because water had been removed from the ocean to form the ice-caps (located chiefly on the continents); secondly, because each ice-cap attracted the remaining ocean water to itself and thus lowered the level of the seas within the tropics. The depth of the platforms, cut-and-built by the waves during maximum glaciation, was estimated to be from 30 to 50 fathoms, or 55 to 90 meters, below present sea-level.

With the late Pleistocene warming of the air, the surface water of the tropical seas grew rapidly warmer, the ice-caps were slowly melted, and general sea-level was correspondingly raised again. The warming of the tropical seas allowed the coral larvæ, emanating from the limited reefs not entirely killed in spite of the Pleistocene chilling, to colonize the new, wave-cut platforms. Since reef corals thrive best on the outer edges of such benches, the new colonies there specially formed reefs, which grew upward as sea-level rose. Of course many larvæ would settle elsewhere on the platforms, as well as in

[1] Alfred Tylor, *On the formation of deltas, and on the evidence and cause of great changes in the sea-level during the glacial period*, Geol. Mag., vol. v (1868), pp. 576–577.

[2] J. D. Dana, *Coral reefs and coral islands* (1872), p. 366.

[3] Thomas Belt, *An examination of the theories that have been proposed to account for the climate of the glacial period*, Quart. Jour. Sci., 2d series, vol. 4 (1874), pp. 448–450.

[4] Warren Upham, *Geology of New Hampshire*, vol. 3, part 3, Surface geology (1878), p. 18 and pp. 329–330.

[5] Albrecht Penck, *Morphologie der Erdoberfläche*, vol. 2 (1894).

[6] E. von Drygalski, Zeit. Ges. Erdkunde, Berlin, vol. 22 (1887), p. 274.

[7] R. A. Daly, *Pleistocene glaciation and the coral reef problem*, Amer. Jour. Sci., vol. 30 (1910), pp. 297–308; *The glacial-control theory of coral reefs*, Proc. Amer. Acad. Arts and Sci., vol. 51 (1915), pp. 158–251.

[8] *Idem* p. 159.

the shore breakers. In general, however, the colonies on or near the outer rims of the wave-formed platforms would thrive better than the inside colonies and the dominant reef would be linear, following the edges of the platforms. The fringing, barrier, and atoll reefs are thus explained as shallow crowns recently built up on wave-formed platforms. The hypothesis inplies that barrier reefs and atolls have not necessarily characterized the warm seas of the pre-Pleistocene periods but represent physiographic forms due to the highly specialized effects of a Glacial period.

THE TESTIMONY OF TUTUILA.

In the discussions and controversies which have raged over the origin of coral reefs, the islands of the South Seas have played an important part, but in all the extensive literature of the subject little mention has been made of Samoa till very recently. This has been perhaps because the Samoan reefs have been thought too simple to contribute much toward the general coral-reef problem. But in the interpretation of obscure and complicated problems, where many uncertain factors enter, it often happens that the truest clues are afforded by some of the simpler, though really typical, manifestations of the phenomena under investigation. It was therefore hoped that a careful study of the reefs of Tutuila, in spite of their simplicity, might still point, perhaps more clearly, toward the true solution of the coral problem than an investigation of the more striking, but also involved, phenomena of the more famous reefs. For these and other reasons it was thought worth while to undertake the investigation of Tutuila. To unravel the past history of Tutuila, which was felt to be essential for the correct interpretation of the reefs, the writer spent three weeks in July 1920 in a geological reconnaissance of the island. This time was devoted solely to those portions of the past story of Tutuila which appeared to have a direct bearing on the problem in hand. Other phases of the geology of the island were passed over.

THE SUBMERGED MARGINAL SHELF.

Tutuila presents some declared physiographic features which are significant and valuable in guiding the investigation. Two characteristics stand out above all others. These are, first, the deeply eroded nature of the land surface, and second, a broad submerged shelf which surrounds the island. The extent of land dissection testifies to the age of Tutuila. The broad marginal platform, being perhaps the most declared physiographic feature of the island, and at the same time the scene of the coral growth, becomes at once the most critical factor in the problem. The history of the coral reefs is locked up in the origin and history of this submerged shelf, and the correct reading of the story written in this shelf becomes all-important.

The submerged platform is admirably shown on the chart of Tutuila prepared by the Hydrographic Office of the United States Navy Department (see Plate A). The chart reveals comparatively shallow water extending outward from the shores for an average distance of about 2.5 miles, beyond which the water deepens very rapidly. At each end of the elongated island the shelf widens greatly. Its southwestern extremity is just 5 miles from Cape Taputapu, while the southeastern corner is slightly more than 5 miles from Utumea Point. The northwestern and

northeastern corners are in the neighborhood of 4 miles from Cape Taputapu and Cape Matatula, respectively. The seaward margin of the shelf is delineated very closely on the chart by the dotted 100-fathom line, though this lies a little beyond the brink on the steep outer slope.

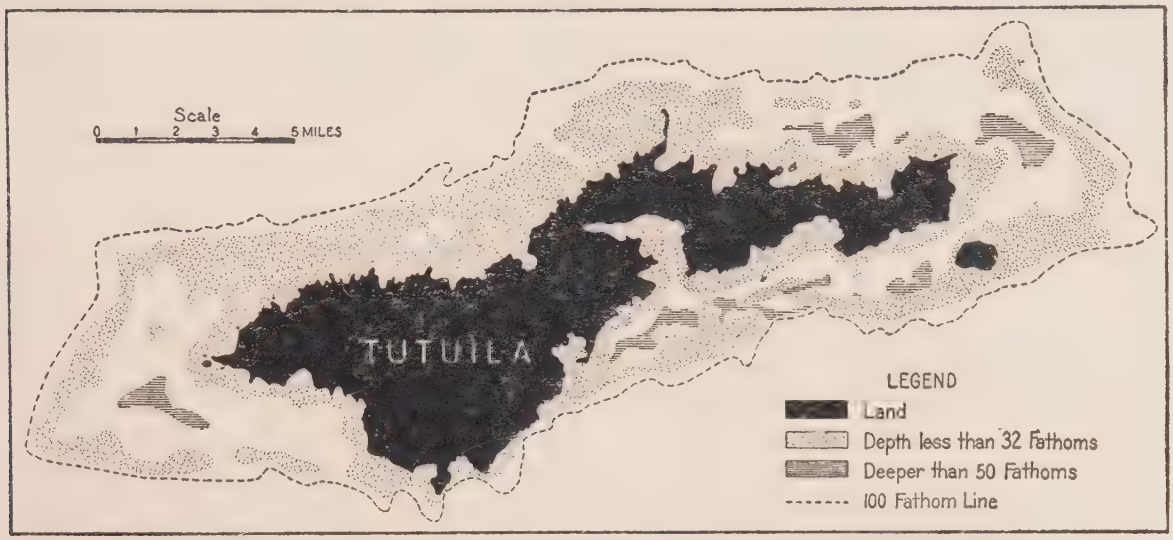

FIG. 4.—Map of Tutuila outlining reefs and deeps. The 32-fathom contour serves to emphasize the highest portions of the old reefs. The reefs in reality are more extensive, occupying, together with their detritus, nearly all the white areas within the limits of the barrier as well.

THE SUBMERGED BARRIER REEF.

In order to render the surface configuration of this shelf readily apparent to the eye, it is necessary to contour the soundings recorded on the chart. This reveals the existence of a more or less strongly developed ridge near the seaward margin of the shelf (fig. 4). Between this ridge and the shore the water deepens considerably. Bottom samples collected by Dr. Mayor show that at least the surface of this ridge is composed of coral line material. Further evidence of the nature of the materials is afforded by the island of Aunuu, a tuff cone perched upon this ridge where volcanic eruptions have burst through it. Embedded in the tuffaceous layers of this cone are numerous fragments of coral rock, indicating that the outbursts which produced the cone have come up through considerable masses of coral-reef material, which of necessity must lie directly beneath the cone. Similarly, the partially dissected tuff cone a mile northwest of Steps Point, though now a part of the mainland of Tutuila in consequence of more recent lava-flows, is in line with the submerged ridge and contains a few coral fragments embedded in the pyroclastic layers. In this section of the ridge also, coral rock must exist in notable quantity.

Because of these facts and because the ridge closely follows the outer margin of the platform, it has been interpreted by Mayor as a submerged coral reef of the barrier type.[1] He has brought out its reef-like character by drawing the 32-fathom

[1] Alfred G. Mayor, *The reefs of Tutuila, Samoa, in their relation to coral-reef theories*, Proc. Amer. Phil. Soc., vol. XIX (1920), p. 5.

contour-line on the chart and coloring the areas standing above this line.[1] Thus portrayed, the reef appears broken into separate strips at a number of places, especially near the northeast and again near the southwest end. This is partly because of the selection of the 32-fathom contour as the dividing-line which, considering the chart as a whole, seemed the best one to bring out the distinctiveness of the reef in its last stage of growth. But if the 40-fathom contour be chosen for the dividing-line, the much greater extent of the reefs becomes apparent, and the barrier is seen to extend continuously around the island, except for a short break of less than a mile, located southeast of Breaker Point.

OLD FRINGING REEF.

The contoured chart shows that in many places the water deepens very gradually for a certain distance from the present shores, and then descends more rapidly to the deeper water between the shore and the old barrier. This indicates a very definite terrace which Mayor has interpreted as an ancient fringing coral reef developed simultaneously with the barrier reef. An alternative hypothesis would be the assumption that it is a submerged alluvial plain. The validity of his hypothesis may be tested by noting the distribution of the alluvium to be expected were it true. This should obviously accumulate by first intent at and near the mouths of the streams in delta fashion. If its quantity is sufficient, it should fill in the bays and build its delta-fronts out to the line of the promontories, and perhaps beyond, before developing sizable flats in front of the promontories. But as a matter of fact the terrace takes on quite a different aspect. Many of the streams enter long reëntrants which show no great amount of filling, while the shallow tract at not a few points is best developed off the ends of promontories. The terrace in general roughly parallels the shore and shows little relation to the stream mouths, but does display some of the irregularity of outline characteristic of coral reefs. As the alternative hypothesis does not seem tenable, this terrace-like form is believed to have been a fringing coral reef.

Growing outward from the shore, the ancient fringing reef has become fused in many places with the barrier reef, obliterating the lagoon between them.[2] This fusion of the reefs occurred most conspicuously on the north side of the island, from the Cockscomb westward almost to the west end of the island, a strip comprising a little less than two-thirds of the north shore. But throughout nearly all of the south side and the two ends of Tutuila, the barrier reef, outlined by the 32-fathom line, is distinctly separated from the fringing reef by deeper water. Since reef-building corals do not thrive in depths greater than 18 to 20 fathoms, and as a large portion of these old reefs is more deeply submerged than this, they are probably surfaced to-day for the most part by dead coral, the reef-builders having been drowned by subsidence of the island.

Daly has suggested that the north side of Tutuila sank less than the south, the lesser submergence on the north permitting the fusion of the outward-growing fringing reef with the barrier.[3] According to his interpretation, the reefs on all

[1] *Idem*, fig. 2. [2] *Idem*, p. 5. [3] Cited by A. G. Mayor, *idem*.

but the western two-thirds of the north side were depressed more rapidly than the corals could build upward and thus became drowned, while on a considerable portion of the north side, where the sinking was less pronounced, the fringing reef was able to fuse with the barrier. If so, the fusion was accomplished early in the history of the submergence, for the fused reef after building up only a few fathoms then became drowned in its turn.

In seeking evidence to support this hypothesis, one finds, however, that the deepest sounding recorded on the chart between the barrier reef and the shore is located northeast of Cape Matatula near the northeast end of the island. Another deep area, reaching down to 50 fathoms, appears farther west on the north side of the island opposite Masefau Bay. This is getting close to the portion of the island which should have sunk less. On the fused reefs of the northern side, small patches of coral bank have grown up to within about 15 fathoms of the present ocean surface, but not much higher; whereas on the south side, which should have sunk most, the Taema bank, a portion of the old barrier opposite Pago Pago Bay, comprises extensive shoals between only 5 and 10 fathoms in depth. East of this, for a mile, is deeper water, and then comes another similar shoal portion of the barrier which extends all the way to the island of Aunuu. Thus the shoalest portions of the old barrier are located on the south side of the island, rather than the north. Furthermore, areas comparable in depth to the shallowest portions of the northern reefs are located at intervals completely around the island. These facts are not altogether in accord with the hypothesis of differential sinking. The subsidence may not have been everywhere the same, but still, if there had been any notable difference in the sinking of the two sides of Tutuila, the 32-fathom line on the chart would hardly serve to delineate the barrier throughout the island. If a depth slightly greater than 32 fathoms be chosen for contouring, the reefs thus outlined will be found at both ends of the island and in places on the south side as well. It is easy to suggest other possible hypotheses, though based on no evidence of a positive sort; but until more positive evidence can be put forth it seems advisable to keep the question of differential sinking an open one.

PRESENT FRINGING REEF.

Since the subsidence which drowned the old reefs and since sea-level came to stand on Tutuila approximately where it is to-day, new fringing reefs have begun to grow outward from the shores. Vigorously growing young reefs flank practically all of the south shore of Tutuila, with the exception of the strip between Point Deceit and Steps Point (known as the "ironbound coast"), where lava-flows have very recently built the land out almost to the edge of the island platform. On the northwest side of the island, however, the new reefs are quite scanty and occur chiefly as isolated patches. Along the south shores and northeast shores, where they are most strongly developed, the reefs extend outward on the average for several hundred yards. The broadest portion of the fringing reef to-day is off Cocoanut Point between Nuuuli and Point Deceit, where, owing to the fact that the surface of a lava-flow now lies slightly below low tide over a wide area, the corals have

found conditions to their liking and have not only built a strong reef along the outer margin of the shoal, but in addition have covered most of the wide flat with their growth (Plate 1, fig. C and Plate 7, fig. B).

NATURE OF THE REEF FOUNDATION.

According to the Darwin-Dana theory, these reefs have grown up from the sloping sides of the volcanic island; according to the theory of planation, they have formed upon an essentially flat floor, cut and built by the action of the sea. The nature of the underlying volcanic-rock surface, therefore, becomes a critical point in the investigation. Does this surface represent the island slope descending rapidly from the present shore and becoming very deeply submerged beneath the outer border of the barrier reef, or is it a relatively level platform which, even at the outer margin, is submerged to only moderate depths? Upon the answer to this question rests the choice between the theory of pure subsidence and the theory of marine planation. Its solution is all-important.

For the solution of this problem, unquestionably the best and most conclusive evidence is that obtained by actual drilling through the reef to the volcanic rock beneath. Drilling at several points in a line running straight out from the shore should give the profile of the underlying surface. Drilling might be expected to be troublesome, because the critical area is now for the most part deeply submerged. But in the evolution of Tutuila the geologic processes have accommodatingly provided a way out of this difficulty. On the south side of the island, between the villages of Nuuuli and Leone, recent lava-flows have spread completely across the lagoon and over the outlying barrier reef, building these lava-flows up above present sea-level and thus extending the land nearly to the brink of the steep abysmal slopes. This fortunate provision of nature makes it possible to drill through the basalt covering, and then through the coral reefs in question, down to the basal surface of volcanic rock. Two or more drillings in a straight line running from the present iron-bound coast just east of Vaitogi toward the old sea-cut cliffs east of Faleniu, now 2 miles inland, should give a decisive answer to the question. Unfortunately an unexpected chain of circumstances made it impossible to do this drilling during the time spent in Samoa in 1920.

In the absence of drill-cores to reveal the exact depth of the reef foundations at selected points, and thus delineate closely the configuration of the underlying basement, recourse must be had to other methods. Though of a less decisive nature, much may still be learned from a study of surface evidence. On the theory of subsidence, as shown in Darwin's figures, the slopes of the volcano should be deeply buried beneath coral accumulations, and the original volcanic rock should not appear *in situ* above the coralline bank. On the marine planation hypothesis, the surface of basement volcanics should lie at more moderate depths and outlying remnants of igneous rock, owing to superior resistance, might be found here and there to have survived the wave attack.

SIGNIFICANCE OF OUTLYING ISLETS.

An examination of the shores reveals numerous tiny islands of this sort which have withstood wave erosion (Plate 2, fig. B). They are composed of flows and pyroclastics similar in each case to the rocks on the adjacent shores, indicating that the flows and tuffaceous beds were formerly continuous across. These detached rocks and islets, however, do not extend very far out from the present shores, for in general the rock formations are too uniform in hardness to allow exposed remnants to withstand the waves very long while the shores behind are retreating and thus adding to their exposure. But their existence, by showing that wave erosion at or near the present level has eaten back the shores of Tutuila certainly for several hundred yards, does clearly extend the original island horizontally for moderate distances at least. If the island history in truth has followed the course prescribed by the Darwinian hypothesis, this cutting back of the shores must have taken place since the postulated subsidence had practically all been accomplished and the waves had begun to beat against the shores at essentially their present level. Whatever hypothesis may be preferred for the origin of the coral reefs, wave-cutting has admittedly been a potent process on Tutuila.

THE COCKSCOMB.

Even though the scattered islets of volcanic rock do not lie far off the present shores, and hence do not necessitate the extension of the island very greatly beyond its present dimensions, so far as they alone are concerned there is, nevertheless, on the north side of the island, a peculiar, lofty, wall-like ridge which extends out halfway across the shelf in question (Plate 3 and Plate 7, fig. A). This ridge constitutes the great promontory just west of Vatia Harbor, and then, after a narrow strip of shallow water where the waves have cut through, it is continued seaward for an additional 0.7 mile as a high, rocky wall named Pola Island on the chart. Because of its rocky teeth and extreme ruggedness, this striking ridge is often called the Cockscomb. It is the most pronounced shore feature on Tutuila. Though 0.7 mile in length, and attaining a height of over 300 feet above tide, Pola Island is barely 100 yards in width.

Considering the strength of the waves that dash against the exposed end of the Cockscomb, it seems a marvel that this slender wall of rock has succeeded in withstanding such attack for the length of time which it clearly must have stood. The explanation is that it is composed of much more resistant rock than the main portion of Tutuila. The rocky wall is found to be an intrusion of trachyte or phonolite, according to Daly,[1] light grayish in color and very dense and hard.

This resistant Cockscomb intrusion would seem to throw much light upon the nature of the broad platform above which it rises so precipitously. Being a dike intruded into preëxistent rocks, it bears evidence of the former presence of continuous rock-masses rising, at the very least, well over 300 feet above present tide-level and continuing seaward from the present position of the north shore

[1] Reginald A. Daly, *The geology of American Samoa*, Carnegie Inst. Wash. Year Book No. 18 (1919), p. 193.

as far as the intrusion can be shown to have extended. If the less-exposed, blunter promontories along the shores have been worn back notable distances by the waves, as is demonstrated by the outstanding remnants which so abundantly dot the coast, this extraordinarily slender promontory in an extremely exposed situation must also have been cut back considerably from its original terminus. So far as the effectiveness of the erosive agents is concerned, it might perfectly well have been whittled back from the very edge of the platform. But in any case the present surviving portion of the Cockscomb intrusion is sufficient to show conclusively that a preëxistent rock mass, hundreds of feet above present sea-level, at one time extended at least halfway out to the brink of the island shelf, and in all probability, considerably farther.

POSSIBLE INTERPRETATIONS.

On the principle of multiple working hypotheses, three different suppositions might be entertained for the nature of the rock-mass into which the Cockscomb dike was intruded: (1) It might have been the continuous mass of the original volcanic island, before notable sea-erosion had occurred; (2) it might have been coral rock accumulated in accordance with the Darwinian, or any other theory of coral-reef development; or (3) it might have been a later lava-flow, or succession of flows and tuff beds, laid down upon an earlier platform which might have been either wave-cut in accordance with the theory of marine planation, or built up of coral material according to the Darwinian conception. Of these, the simplest and most natural case is undoubtedly the first, namely, an intrusion directly into the old volcanic island mass. But the other possibilities have also to be considered.

Let us first follow to its conclusions the second hypothesis, i. e., that the dike was intruded into coral rock. If Tutuila did, in reality, follow the Darwinian chain of events, and develop the broad fringing shelf through the accumulation of a vast amount of coralline and other deposits, then the coral platform into which the dike was intruded must have stood at one time more than 300 feet above present sea-level, or at least 500 feet higher than the surface of the present submerged reef adjacent to the Cockscomb, for that is now under 30 fathoms of water not far away. Were this the case, it would seem that some remnants of this limestone should still remain somewhere on the island. On certain other Pacific islands, such as members of the Fiji and Hawaiian groups, elevated reefs are conspicuous to-day. But no portions of any elevated reef have ever been found on Tutuila, or even detached fragments of coral rock beyond the reach of the present hurricane waves.[1]

In the second place, granting the existence of such a postulated elevated reef, it would still be necessary to reduce the coral surface, throughout its entire 2.5 miles of width, to its present level, presumably by marine planation. This, in effect, would make the shelf truly a product of marine planation, even though, to be sure, it be planation of coral-reef material instead of volcanic rock. On that

[1] The scattered fragments of reef-rock embedded in the layers of the tuff cone of Aunuu and the one near Steps Point are of course excluded.

abrasion plain, cut through coral rock, the observed barrier reef would then have to grow up much as held by the familiar hypothesis of marine planation. The fact that to-day the deeps between the submerged reefs extend to depths of more than 60 fathoms would necessitate planation to even greater depths than above stated, as will be brought out later.

The third hypothesis avoids the troublesome fact that elevated coral rock is not found on Tutuila, by postulating later lava-flows and tuff deposits, instead of high-level coral reefs. It would say that a broad platform had been built up from the sloping surface of the original island through the accumulation of a great quantity of coral rock and associated deposits, and that successive flows and pyroclastics were spread upon this coral shelf, building it up for at least 300 feet more. Into this accumulation of limestone in the lower portion and volcanic rocks above, the Cockscomb dike was then intruded at a comparatively recent date in the history of the island. While the absence of elevated reefs may thus be explained, this supposition does not dispense with marine planation. In fact, the volcanic rocks of this hypothesis, unless weaker than the present surface rocks of Tutuila, would lay a more severe tax on the cutting power of the waves than the softer coral-reef material. This difficulty might possibly be dodged in part by assuming that sea-level was then sufficiently low, relative to the island, to encounter the underlying reef-rock rather than the overlying resistant volcanics, and to accomplish the result by undercutting, though the tumbling volcanic blocks, in consequence of the undercutting, would tend to shield the coral material from further cutting at so rapid a rate. But if there ever were such later volcanic accumulations in the Cockscomb region as required by this hypothesis, it would seem probable that some recognizable evidence of their former extent should still exist. No such evidence has yet been noted on the north shore of Tutuila.

THE FAVORED INTERPRETATION.

The three alternative hypotheses are therefore less radically different in their ultimate significance than they seemed on first inspection, and perhaps need not be discussed at greater length. For in any case, whatever the antecedents may have been, the marginal portion of Tutuila has been brought to its present condition by wave action, followed by the building of the barrier reef, now deeply submerged. As the two hypotheses which require specially postulated conditions appear to face, in addition, serious difficulties, we are left with the simplest hypothesis, i. e., that the Cockscomb trachytic or phonolitic pod, now rising high above the waves, was intruded into the original island mass. Such being the case, we are led to believe that the marine abrasion surface, upon which the reefs have been built, is one cut for the most part in the volcanic rocks of the original island. Its minimum extent should be from the present shore seaward as far as the outer point of the present Cockscomb, which is fully halfway to the margin of the platform. In all probability it extends not a little farther, though it is not easy to say how much of the outer half of the shelf should be wave-cut and how much wave-built.

PRESENT DEPTH OF BASAL PLATFORM.

It is next in order to determine the level of the probable wave-cut and wave-built platform. If we examine the chart of Tutuila, it will be seen that the deepest soundings recorded between the submerged barrier and the shore are located in strips whose longest dimensions are more or less parallel to the shore. Though some of them branch in various directions and develop considerable irregularity of outline, nevertheless the long dimension is prevailing concentric with the margin of the shelf and the island shores alike. These hollows are irregularly distributed on both sides of the island, though naturally absent from the region where the fringing and barrier reefs have become fused.

Do these deeps represent erosion, or have they resulted from the action of constructional agents? If due to the work of running water on land, their long dimension should be at right angles to the margin of the island instead of parallel to it, for on a steep-sided island like Tutuila the streams should flow rapidly to the sea. On the other hand, submarine scour would certainly not be expected to develop deeps so persistently oriented with respect to the margin of the shelf and yet so irregularly scattered along it. The depths from point to point are also too irregular to harmonize well with the hypothesis of scour by ocean currents. The deeps seem quite clearly to be the outcome of constructional rather than degradational processes. Coral action has built up reefs and left the deeps as inter-reef areas more nearly representing the level of the basement platform. The characteristic irregular growth of corals explains their irregular outlines and scattered locations. Their long dimensions are parallel to the shores because determined by the barrier reef on one side and the fringing reef on the other.

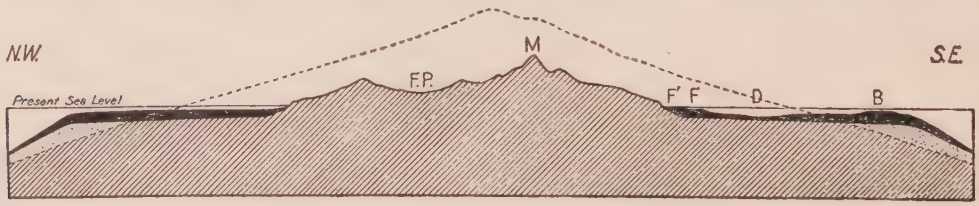

FIG. 5.—Section across Tutuila from northwest to southeast. Drawn to true scale. M, peak of Matafao. F.P., Fagasa Pass between Pago Pago and Fagasa. B, barrier reef. D, deep. F, drowned fringing reef. F′, present growing fringing reef. Shaded area, volcanic rock. Stippled area, sediment (perhaps including coral material), constituting wave-built platform. Solid, black, coral reefs and coral detritus. Broken line, hypothetical profile of original island.

If, in truth, these deeps represent the areas which have been built up least by coral growth, they should give the best readily available index of the level of the basement platform upon which the reefs have been built. They may, and probably have, received some filling, partly of coral débris from the adjacent reefs, partly of organic deposits of other types, and also to some extent land-derived silt, though the vigorous growth of coral in the fringing and barrier reefs would suggest that mud was not received in very great quantities However much filling they may have received, these deeps come nearer than any other available evidence, except actual drilling, to telling us the desired level of the basal shelf.

The greatest depth reported on the chart inside the barrier reef is 68 fathoms, located off the east end of the island, 1.5 miles northeast of Cape Matatula. On the south side of the island a depth of 66 fathoms is reported in the long, narrow deep about 2 miles east of Breaker Point. If the present surface of the submerged shelf has been fashioned chiefly by constructional agencies after the earlier planation, we should then take these maximum depths as mostly closely approximating the present minimum depth of the old platform. On the basis of these figures, the volcanic floor which affords foundation for the coral superstructure would therefore, at the present time, lie at least 400 feet below the surface of the ocean. It may be very considerably more, for it was not possible to determine how much filling there may have been in these deeps (fig. 5). The minimum depth of the basement platform will be taken as 400 feet below sea-level.

ERODED CONDITION OF THE ISLAND.

From the deck of the arriving steamer the scientific visitor to Tutuila is promptly impressed by the numerous coves along the shores, the deeply carved valleys leading to the coves, and the great extent to which the original constructional slopes have been modified by the agents of denudation. If later he crosses the island by one of the mountain trails, he marvels at the extreme sharpness of the island watershed. Viewed from the summit of Matafao, the highest peak on Tutuila, the island is seen to be a mere skeleton of its former self, with sharpened backbone threading its way to the east and to the west. The imagination is stirred by the amount of chiseling which must have been required to carve a rounded volcanic island into the trenched and peaked and edged forms which are stretched out before one in panorama. As the numerous swift streams on opposite sides of the island have cut their deep valleys steadily headward, the divides between them have become narrower and narrower till the majority of them are now at about their maximum sharpness. With further passage of time they can only become lower.

FORMER HEIGHT OF TUTUILA.

That the toplands of Tutuila originally were higher than now is perfectly evident from the fact that the highest peaks to-day, such as Matafao and Pioa, have been carved from intrusive masses which penetrated the volcanic series. The surrounding rocks having been swept away, the more resistant intrusives have better withstood the denudation and now overtop the rest of the land-surface. The heights to which Tutuila formerly towered are, however, entirely unknown, but it is possible, by making certain assumptions, to determine the range of possibilities. The average width of the platform above the 100-fathom line is now approximately 8 miles, but this width probably includes some depositional extension of the shelf beyond the border of the original volcanic island. Suppose we allow half a mile for the average width of the wave-built extension of the island. Then constructing a hypothetical island 7 miles wide with regular slopes of 10°, we find that the culminating ridge in the median line of the island should have been

a height of about 3,250 feet above sea. Allowing slopes of 15° and 20°, it should reach heights of 4,950 feet and 6,720 feet, respectively.

Where much pyroclastic material enters into the composition of a volcanic island, the original slopes are steeper than where made up entirely of basic lava-flows. The recent tuff cone of Aunuu is made of layers resting between 30° and 35°. But Tutuila, because of the much greater proportion of basaltic flows, must have developed gentler slopes, though near the mouth of Vatia Bay some layers of volcanic breccia exhibit the steep inclination of 35°. An average of all the dip-readings which were taken along the coast of Tutuila was found to be about 14°. An average angle of 14° would mean that Tutuila may once have stood more than 4,000 feet above the sea (fig. 5). Layers more steeply inclined, near the middle of the island, building up a central cone, or cones, might add somewhat to this height. In general, it was found that the flows and pyroclastic layers lie more steeply in the middle portion of the island and less steeply toward the two extremities.

Near the western end of the island, a portion of the original constructional surface appears to have largely escaped the extensive denudation. North of the village of Leone, the rugged backbone of the island flattens out into a distinct table-land over a mile in length and more than a half mile in breadth. This flattish area, between the 1,200 and 1,300 foot contours, is interpreted as the surface of a lava-flow. Lateritization of its surface materials has progressed much farther than in most other portions of the island. Eastward this flat rises rapidly to the peaks of Oloava (1,501 feet) and Olotele (1,639 feet). A narrow remnant of this flat continues the divide westward for another mile and then descends quickly to Cape Taputapu (West Cape) at the extremity of the island. This original constructional surface seems to have escaped notable erosion owing to its flatness, while the higher portions of the island to the east, because of steeper slopes, have suffered greatly. Streams working back from both the north and south shores have cut deep valleys heading into it. If this flattish lava surface be projected both north and south, it will be seen to extend far out to sea before dipping beneath the waves. Unless the portion of this surface now gone sloped seaward considerably more rapidly than that remaining, this surface could hardly have reached sea-level at the outer edge of the submerged shelf.

THE DROWNED VALLEYS.

Meteorological observations at the naval station in Pago Pago have placed the average annual rainfall there at 191 inches. A consequence of this very heavy rainfall is an abundance of streams on Tutuila, the great majority of which have deep valleys and enter well-developed bays. Because of the form of many of these bays and their relation to the streams and valley sides, they have been interpreted as drowned valleys. Their general similarity indicates essentially similar past conditions throughout the island. The streams descend swiftly from the watershed and have cut deep, narrow, sharply V-shaped valleys which continue as such nearly to sea-level. Upon nearing sea-level, each of the larger of these sharply cut valleys opens out, without any intermediate stages, into a wide alluvial plain

sloping gently to the sea. The alluvial flat widens steadily seaward from its beginning in the narrow river-bed and reaches its greatest breadth at the seashore. The valley walls, becoming farther and farther apart, continue steep and run out into the adjoining promontories. It is on these alluvial plains, at the heads of the bays, that the majority of the native villages are located for, with the exception of portions of the recent lava-flow between Nuuuli and Leone, there is little other land on Tutuila suitable for village sites (Plate 5).

The relation of the alluvial flats to the steep valley sides is clearly that of a filling subsequent to the valley excavation. The valley sides must clearly continue beneath the filling for several hundred feet before the convergence will restore the V-shape which erosion imparted. The valleys have been cut at a time when the strand-line on Tutuila stood at least several hundred feet lower than at present. They were doubtless developed in adjustment to sea-level during the later stages of the cutting of the broad marginal platform, now more than 400 feet below tide. With the subsequent rise of sea-level relative to Tutuila, the lower parts of the valleys became drowned, forming the numerous bays, while the sea, by checking the velocity of the streams, caused deposition in delta fashion at the heads of the bays. As the deltas advanced into the bays, their top-set beds were gradually built up to sea-level and afterwards into the gently sloping gravel plains as the streams shifted from time to time.

SEA CLIFFING.

The effectiveness of wave attack against the shores is well shown by the strongly clift character of the promontories throughout the island. Several of these sea-cliffs rise fully 500 feet above tide. But the heights of the present cliffs can not be taken as a safe measure of the distances which the headlands have retreated before the wave attack, for, as the cliffs recede, the rapid subaerial denudation lowers the sloping crest-lines of the promontory ridges. The present cliffs show that the cliffing by the waves keeps somewhat ahead of the lowering of the island by denudation. But no quantitative statement will be attempted.

At the base of these cliffs a well-developed wave-cut bench on nearly all the promontories of the island demonstrates that sea-level has recently stood somewhat higher relative to Tutuila than it does at present (Plate 6). Dr. Mayor has given the elevation of this bench above high tide as 8 feet;[1] in not a few places, however, it rises higher than this—to 10 or 12 feet. It has also a pronounced slope toward the sea. Because of its variable height, the round number of 10 feet will be used in this description. This figure can not, however, be taken as representing exactly the amount of shifting of sea-level, for the reason that the bench presumably was not cut at high-tide level. According to D. W. Johnson, the typical wave-cut bench in both the early and the more advanced stages of development slopes seaward from above the high-tide shore-line to slightly below and beyond the low-tide shore-line, where it may either end abruptly or may gradually decrease in slope

[1] Alfred G. Mayor, *The reefs of Tutuila, Samoa, in their relation to coral-reef theories*, Proc. Amer. Phil. Soc., vol. XIX (1920), pp. 2–4.

until it merges imperceptibly into the more extensive, nearly horizontal abrasion platform produced by long-continued wave erosion.[1] Near the high-tide shore-line the bench slopes strongly seaward, but at the low-tide shore-line the slope has become much less.

RECENT EMERGENCE.

According to this analysis, the portions of the seaward-sloping Tutuila benches which come nearest to horizontality should have been cut not far from the former low-tide level. If this be true, these benches might indicate a change of sea-level of perhaps 12 to 15 feet. Daly, however, is inclined to place the measure of recent emergence in Samoa at about 20 feet.[2] His argument is based upon several sea-caves whose floors vary from 14 or 15 feet above high tide at their mouths to 25 feet at the back walls. He states that the lower lips of caves being formed at the present time are characteristically 4 to 6 or more feet below high-tide level, and that the floors rise inward to a few feet above high tide. He believes that an emergence of 20 feet would just fit the 8-foot benches, since the cliffs now being cut on the Samoan headlands (where not protected by coral reefs) have regularly about 12 feet of water directly at their feet during high tide.

We may, therefore, conclude that these sloping benches of Tutuila were cut while the strand-line stood somewhere from 12 to 20 feet higher than at present. Benches, or beaches, at corresponding elevations, mark the shores of members of the Hawaiian group and various other Pacific islands; they appear at many places along the eastern coast of Australia[3] and have been noted in many other parts of the globe. From the widespread occurrence of sea benches and beach deposits at about this level a general or worldwide sinking of ocean-level has been inferred.[4]

Dr. Mayor had already come to the conclusion that when the sea was at this high level and was cutting the elevated bench, there were no coral reefs growing around Tutuila.[5] A careful search for elevated reef material, both upon the benches of the exposed headlands and within the more sheltered embayments, revealed no trace whatever of coral material in place. The stream-banks which expose shallow sections of the alluvial fillings at the heads of the bays were also searched in vain for coral rock. But it is also to be noted that in the creek sections practically no beach material of any sort was identified more than a few score feet back from the present beach, although scattered fragments of coral rock cast up by hurricane waves are now strewn over the surface of these flats for a hundred yards or more from the beach. With the exception of these scattered fragments, the material of these delta plains which can be seen in exposures to-day consists almost exclusively of stream deposits and torrential wash.

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[1] Douglas W. Johnson, *Shore processes and shoreline development* (1919), p. 162; pp. 202–203; figs. 22 and 23.

[2] Reginald A. Daly, *A recent worldwide sinking of ocean-level*, Geol. Mag., vol. LVII (1920), p. 249.

[3] E. C. Andrews, *New South Wales Handbook*, Brit. Assoc. Adv. Sci. (1914), pp. 525–526, 532; C. A. Sussmilch, *Introduction to the geology of New South Wales*, second edition (1914), p. 222.

[4] L. A. Cotton, personal communication; R. A. Daly, *A recent worldwide sinking of ocean-level*, Geol. Mag., vol. LVII (1920), pp. 246–261; *A general sinking of sea-level in recent time*, Proc. Nat. Acad. of Sci., vol. 6 (1920), pp. 246–250.

[5] A. G. Mayor, *The reefs of Tutuila, Samoa, in their relation to coral reef problems*, Proc. Amer. Phil. Soc. (1920), pp. 3–4.

THE INTERPRETED HISTORY.

A reading of Tutuila's geologic past, from the present-day forms and features above described, points toward the following sequence of events: Long-continued volcanic eruptions coming from beneath the floor of the Pacific built the island up to sea-level and finally several thousand feet above tide. The agents of denudation, both marine and subaerial, must have been constantly at work on this island during its growing stages, but at that time building exceeded tearing down. But when the growth became essentially complete with the slackening of vulcanism, erosion became dominant. The waves cut into the shores, cliffing them, and constructing the combined wave-cut and wave-built platform. The presence of various weak layers of volcanic tuff interspersed between more resistant basaltic flows hastened the destructive work of the sea, while if coral growth developed reefs of any moment, their protective effect would serve to diminish the rate of shore erosion. At the same time, streams and slope-wash actively attacked the land slopes. The heavy tropical rainfall favored rapid erosion by running water, though the dense tropical vegetal covering did its best to retard the process.

Whatever the exact conditions may have been, and whatever fluctuations and interruptions there may have been in the operation of these agents with changing conditions, they ultimately did accomplish notable results. Running water has worn down the island, at least in the central and eastern portion, to a fraction of its original height. The broad shelf has resulted partly from this and partly from the work of the sea. During most of the time while these processes were operating sea-level stood at least 400 feet lower on the shores of Tutuila than at present. Not only was the shelf formed at such a level, but the present drowned and alluvial-filled valleys indicate also that they were cut in adjustment to such a level. Estimates of the extent of the drowning, by the method of projecting the valley slopes downward to intersection, are rather uncertain, but the results obtained by this method point to a depth considerably in excess of 400 feet.

To what extent corals grew and produced reefs upon the shelf during its development is uncertain. There are many possibilities involved, some of which will be discussed later. In any case, a barrier reef developed near the outer margin of the shelf during the later stages. Since the base of this reef lies at a minimum depth of some 70 fathoms, and as the top rises to within less than 30 fathoms of the surface over most of its extent, much upward growth is necessarily implied. A fringing reef also came into being along the shores. Over all but a portion of the northern side of Tutuila the fringing reef has remained quite distinct from the barrier, leaving a wide lagoon of deeper water between. But over nearly two-thirds of the north shore the two reefs have become fused as interpreted by Mayor.

During the formation of these reefs the sea must have been creeping higher and higher upon Tutuila, as indicated by the vertical thickness of coral. Further subsidence followed the building of the reefs, for they are now deeply submerged. This subsidence may have taken place so rapidly that the corals could not main-

tain themselves and for the most part died out. On the other hand, it is possible that the growth of the old reefs was stopped by adverse conditions in connection with the fluctuating sea-level of the glacial period. The evidence at hand, however, is not thought sufficient to decide between the various possibilities.

Since the building of the barrier reef, explosive vulcanism has developed the three tuff cones which rest upon it and contain within their layers broken fragments of coral. One of these constitutes the island of Aunuu; the other two are the partially broken-down craters near Steps Point. Since the 10-foot wave-cut bench shows nowhere to better advantage than in the breach of the crater-walls at the eastern extremity of Aunuu, it is clear that this volcanic activity occurred previous to the high-water stage.

The general subsidence continued until the sea stood from 12 to 20 feet higher upon the shores of Tutuila than at present, as indicated by the prevalent 10-foot benches on the headlands. The submergence may have been more or less steadily progressive, or there may have been various oscillations of sea-level during the interval. Extensive drilling through the young fringing reefs along the shores, by revealing the presence or absence of lower benches, might be expected to throw light upon this portion of the history. Though no positive evidence of coral reefs around the shores of Tutuila at this high-water stage has yet been discovered, Mayor found a reef 8 feet above high tide on Rose Atoll, at the eastern extremity of the Samoan group,[1] and there were also coral reefs connected with the elevated benches of corresponding height on the Hawaiian island of Oahu.

The most recent movement of the strand-line has been downward, probably a part, as Daly thinks, of a world-wide lowering of sea-level in which Tutuila played chiefly a passive part. Since this moderate drop of sea-level, the new fringing reefs have grown to their present size. Within the same period of time have come the extensive lava outbursts between Leone and Nuuuli, which, after filling the lagoon and covering the barrier reef, have extended the land at some points nearly to the edge of the shelf. Though this occurred comparatively recently, soil has accumulated from the weathering of the basalt and the vigorous sea-waves on the exposed coast have cut back many yards into the solid flows, as evidenced by the outlying remnants.

THE BEARING ON CORAL-REEF THEORIES.

It remains finally to discuss the bearing of these Tutuila studies upon the various coral-reef theories.

THEORY OF SOLUTION.

The Murray-Agassiz theory of solution is dependent upon the ability of sea-water to dissolve calcium carbonate under the conditions existing in tropical seas. But various investigators have recently shown conclusively that the alkaline water of the tropical seas is unable to do this. Drew has shown that, through the operation of denitrifying bacteria, calcium carbonate is now being precipitated

[1]Alfred G. Mayor, Carnegie Inst. Wash., Year Book, 1920, p. 187.

in enormous quantities in the lagoons of the Florida key region.[1] The lagoons are being filled with calcareous accumulations, the deposition of sediment exceeding its removal.[2] Dole's chemical investigations upon the character of the sea-water at Tortugas have indicated that free carbon dioxide is entirely absent and that the water is therefore unable to dissolve more calcium carbonate by virtue of free carbon dioxide.[3] Vaughan, in summarizing the evidence, concludes that the results of other lines of inquiry which he has conducted are so positive that the formation of lagoons by submarine solution may be definitely eliminated from consideration.[4]

Admitting this, it has still been argued that rain-water falling upon a densely forested volcanic island might have its acidity so increased as to dissolve the shoreward portions of an encircling coral reef. For the effective operation of this principle, a more favorable choice than Tutuila could hardly be made, for it possesses no elevated coral reefs, or limestone beds above high-tide, from which the streams might obtain calcium carbonate, while humic acids from decomposing vegetable matter should be about as abundant there as anywhere on the globe. But Dr. Mayor's careful investigations, both on Tutuila and on Oahu, have shown that, while the rain-water there is indeed acid, having a hydrogen-ion concentration ranging from 0.126 to 0.678 $\times$ 10^{-5}, the streams and springs of these two islands are usually slightly alkaline, due to bicarbonates. Determinations of the water from eleven of the principal streams and six springs on Tutuila gave an average of 7.19 P H or 0.645 $\times$ 10^{-7} hydrogen-ion concentration, the range[5] being from 0.25 $\times$ 10^{-6} to 0.38 $\times$ 10^{-7}. This alkalinity is an outcome of the rapid carbonation of the basic volcanic rocks by atmospheric carbon-dioxide in the process of weathering. Because of this, Mayor has expressed the conclusion that "the surface waters draining off from Tutuila and Oahu, being alkaline, can not dissolve limestone by reason of their acidity, and the Murray-Agassiz theory of solution of the shoreward parts of reef flats by fresh water is not supported."[6]

THEORY OF SUBSIDENCE.

The time-honored Darwin-Dana theory of the origin of coral reefs makes subsidence its keynote. If we take this theory in its type form, it would maintain that the barrier reef of Tutuila has been built up from the sloping sides of the volcanic island. If, however, the conclusions of the present study be justified, the case of Tutuila has not been so simple. The reef instead has formed on a wave-cut and wave-built shelf averaging more than 2 miles in breadth. Tutuila to this

[1] G. Harold Drew, *On the precipitation of calcium carbonate by marine bacteria, and on the action of denitrifying bacteria in tropical and temperate seas*, Carnegie Inst. Wash. Pub. No. 182 (1914), pp. 7–45.

[2] T. W. Vaughan, *Corals and the formation of coral reefs*, Smithsonian Report for 1917, p. 225; and earlier papers.

[3] R. B. Dole, *Some chemical characteristics of sea-water at Tortugas and around Biscayne Bay, Florida*, Smithsonian Report for 1917, pp. 71–78.

[4] T. W. Vaughan, *Sketch of the geologic history of the Florida coral-reef tract and comparisons with other coral-reef areas*, Jour. Wash. Acad. Sci., vol. 4 (1914), pp. 26–34.

[5] Alfred G. Mayor, *Coral reefs of Tutuila, with reference to the Murray-Agassiz solution theory*, Proc. Nat. Acad. Sci., vol. 3 (1917), pp. 522–526.

[6] *Op. cit.*, p. 524.

extent—and this seems to be one of the most debated points—does not conform to the Darwin-Dana theory in its ordinary form. But it was entirely characteristic of the far-seeing vision of the great originator of this theory that he anticipated the possibility of reefs developing upon surfaces of planation as well as surfaces of original deposition. But as he did not know of such a case, this possibility was not put to the fore. Had Darwin realized the full importance of marine planation, he could easily have enlarged his theory to include the Tutuila type.

The theory of subsidence alone requires a considerable vertical thickness of reef. On the assumption that the original slopes of Tutuila averaged 15°, this rate of descent in 2 miles would carry the surface down to 2,830 feet below tide-level. Assuming a slope of 10°, the volcanic rock would be submerged 1,860 feet at a distance 2 miles from shore. The presence of an antecedent marginal platform does not necessitate such a thick upward growth of coral to build the reefs up to their present level.

The interpretation of Tutuila requires considerable subsidence, which is the principal tenet of the Darwin-Dana theory. A minimum estimate places the plain of abrasion 400 feet below present sea-level. It is possible that it lies considerably deeper than this, but how much deeper can not readily be told, because it is difficult to estimate the amount of filling which has occurred in the deeps still remaining on the submerged shelf. Such filling would be in part fragments detached from the adjacent reefs, in part sediment from the island, and in part organic deposition from algæ, foraminifera, and other organisms living in the waters inclosed by the barrier. Skeats has pointed out the importance of organic deposition within the lagoon of Funafuti atoll, which seems to be steadily filling up.[1] On the other hand, the slender Cockscomb wall, which projects so high above the plain of abrasion, would seem to favor the belief in as moderate a depth as is consistent with the other facts. But in any case 400 feet, the very least depth which can be assigned to the abrasion plain, is too far below the surface to permit the belief that the platform was cut under the conditions of glacial control without subsidence. If in truth the plain lies considerably deeper than 400 feet, just so much more subsidence is required.

THEORY OF GLACIAL CONTROL.

According to the glacial-control theory as originally put forth and as generally understood, the reefs have been developed on platforms cut by the waves during lowered sea-level in consequence of the formation of the ice-caps, and when, because of the chilling of the seas and the resulting reduced coral growth and diminished protection of the shores, the sea-waves were unusually effective in their attack on the oceanic islands.[2] Daly placed the lowering of the tropical seas due to the abstraction of water from the oceans to supply the glaciers during maximum Pleistocene glaciation, together with the added gravitative influence of

[1] Ernest W. Skeats, *The coral-reef problem and the evidence of the Funafuti borings*, Amer. Jour. Sci., vol. XLV (1918), pp. 81–90.

[2] Reginald A. Daly *Pleistocene glaciation and the coral-reef problem*, Amer. Jour. Sci., vol. 30 (1910), pp. 297–308; *The glacial control theory of coral reefs*, Proc. Amer. Acad. Arts and Sci., vol. 51 (1915), pp. 158–251.

the ice-caps, at 60 to 70 meters.[1] Humphreys's estimate is 67 meters.[2] The benching should therefore have occurred between 180 and 250 feet below present sea-level, on the assumption that the greater part of the cutting took place during the times of maximum extent of the ice-sheets and corresponding lowest levels of the ocean.

Glacial geologists, however, will be impressed at the outset with the scant justice accorded the interglacial epochs. They are very lightly passed over, and the impression is given that the sea was actively attacking the coasts at the lowered levels throughout nearly the *whole* glacial period.[3] "As already observed, the wave abrasion began before the climax of the Kansan stage and continued without serious interruption until the Wisconsin climax—a period estimated at 280,000 to 900,000 years."[4] It is, however, held by most students of Pleistocene glacial phenomena that the interglacial epochs were longer than the glacial epochs, and each interglacial epoch longer than the time since the Pleistocene.

To ascertain in a quantitative way the present consensus of American opinion on the apportionment of Pleistocene time, a questionnaire was sent to the ten American geologists who, in the writer's opinion, seemed best qualified to estimate the duration of the separate stages. The figures expressing the views of these ten glacial geologists were then averaged. The composite result is that if the sum of glacial epochs of the Pleistocene be taken as 1, total Pleistocene interglacial time would have to be represented by 5. In addition, the individual interglacial epochs were not only much longer than the corresponding glacial epochs, but each interglacial epoch was also very much longer than all post-glacial time. In each of the first three epochs of deglaciation, the weathering of the upper portion of the last-laid drift proceeded to such extremes as to develop the remarkable residual accumulations of gumbotil, so splendidly described by Kay, whereas in the shorter time since the retreat of the Wisconsin ice-sheet there has been no approach to the complete weathering necessary to develop gumbotil.[5]

It is also well known that the climate in one or more of the epochs of deglaciation was warmer than that of to-day.[6] Because of this, and because all the time since the climax of the Wisconsin glaciation is but a small fraction of the duration of either the first, the second, or the third interglacial epoch, it is in fact a mooted question whether we may not be living to-day in an interglacial epoch. But in any case, however much the conditions to-day represent a relief from the rigors of the Wisconsin glaciation, the much greater duration of certainly the Aftonian, Yarmouth, and Sangamon, and probably the Peorian, interglacial epochs, and the recognized warmer climate of at least one and possibly more of these stages, would imply still greater swings of the pendulum from glacial conditions at those times. The full measure of all that has happened since the climax of the Wisconsin stage,

[1] Proc. Amer. Acad. Arts and Sci., vol. 51 (1915), p. 174.
[2] W. J. Humphreys, *Changes of sea-level due to changes of ocean volume*, Jour. Wash. Acad. Sci., vol. 5 (1915), pp. 445–446.
[3] R. A. Daly, *op. cit.*, p. 180.
[4] R. A. Daly, *op. cit.*, p. 181.
[5] George F. Kay and J. Newton Pearce, *The origin of gumbotil*, Jour. of Geol., vol. XXVIII (1920), pp. 89–125.
[6] T. C. Chamberlin and R. D. Salisbury, *Geology*, vol. III (1906), pp. 490–493.

and more, may be attributed to each of these interglacial stages. Coral protection of the shores of tropical islands should, so far as these particular physical factors are concerned, have been as adequate as to-day, and perhaps more so. Vaughan, indeed, has brought out the fact that Pleistocene reefs were extensively developed in Central America, the West Indies, and Florida in the same areas where living reefs exist to-day, whereas in Pliocene times there had been only a weak development of reef corals in these regions.[1] Mayor furthermore states that the Pleistocene coral reefs east of the entrance to Santiago, Cuba, were richer than those now living there.[2]

According to the composite estimate of the ten American glacial geologists, about one-fifth of the entire Pleistocene period experienced glacial conditions. But a large portion of this fifth of the Pleistocene was consumed in the advances and retreats of the ice-sheets, for the glaciers presumably stood at their maximum stage only for limited lengths of time. The same glacialists were also kind enough to contribute estimates on the relative lengths of time to be assigned to the advancing stage, the stage of maximum extent (allowing an oscillation of the ice borders of perhaps 25 miles), and the retreating stage. But only seven of the ten committed themselves definitely to figures; an average, however, of the seven estimates is as follows: Advancing stage, 41 per cent; maximum stage, 20 per cent; retreating stage, 39 per cent. Accordingly, an apportionment of the whole Pleistocene would give the following:

	p. ct.
Combined stages of maximum glaciation	4
Combined stages of advancing and retreating ice-sheets	16
Total of interglacial epochs	80
Total Pleistocene time	100

So far as glacial control alone is concerned, the wave-attack on the shores of the coral islands should therefore be in percentage of Pleistocene:

	p. ct.
Cutting at lowest levels (glacial control)	4
Cutting at intermediate levels	16
Cutting at essentially present level (interglacial epochs)	80

But in nature other factors would enter to complicate the case and blur the record. During the long period of time represented by the Pleistocene, changes of sea-level due to causes other than glaciation would, in all probability, intervene to shift the strand-lines, to some extent at least, and thus more or less mask the effects of alternating glacial and interglacial epochs. In particular cases diastrophism may well have caused a greater shifting of the strand-line than glaciation. In such cases the difficulty of determining the true rôle played by glacial control would be greatly increased.

In summation, the chief point to be emphasized is that during four-fifths of Pleistocene time the wave-cutting was going on at the present level, except as modified by other factors than glacial control; that during 16 per cent of the glacial

[1] T. W. Vaughan, U. S. Nat. Mus. Bull. 103 (1919), p. 226.

[2] Personal communication.

period the waves operated at levels intermediate between present sea-level and the lowest glacial strand-line; while the cutting at the lowest level due to glaciation was in progress during only about 4 per cent of Pleistocene time. The brief duration of the low-level glacial-control wave-attack must greatly lessen its importance as a factor in the erosion of oceanic shores.

It has recently been urged by Ulrich that the removal of ocean-water to form the ice-sheets, instead of lowering sea-level in the tropical regions, would, because of the temporarily diminished capacity of the ocean basins owing to an isostatic bulging of the sea-bottom adjacent to the border of the ice-sheets, actually cause a *rise of sea-level*, except in the areas immediately affected by the ice-sheets.[1] This unfortunate conception may easily be put to the quantitative test. To concede everything possible, we may allow perfect isostasy, which is obviously granting too much. The average density of the outer part of the lithosphere is fully 2.7, and the bulge is made of rock and not water. Each gram of water taken from the ocean and piled on land had a volume of 1 c. c.; but the corresponding gram of rock which participates in the peripheral bulging has, in consequence of its greater specific gravity, a volume of only 0.37 c. c. Hence the lessening of the capacity of the ocean basins, even on the assumption of complete isostatic compensation, could amount only to 37 per cent of the volume of the water removed.[2]

Furthermore, an inspection of the maps of Pleistocene glaciation will show that about half of the bulging peripheral to the ice-sheets should have occurred on land and not in the ocean, and so should not have affected the capacity of the ocean basins, except possibly indirectly and very remotely. The diminished capacity of the ocean should then equal only 18 or 19 per cent of the volume of water removed, even on the assumption of complete isostasy, and in reality the process would fall not a little short of this. Instead of producing an actual general rise of sea-level, the most that can be attributed to isostatic bulging, even under generous assumptions, is to lessen the general lowering of sea-level due to glacial accumulations on land by about one-sixth. Inasmuch as the limit of error in estimating the amount of lowering of sea-level to be expected at the times of maximum glaciation is doubtless greater than one-sixth, no modification of the figures used by Daly will be introduced in this paper.

Another possible modification of the estimate of sea-level lowering due to glaciation results from the changing rate of the earth's rotation in consequence of the shifting of water from lower to higher latitudes. The ultimate source of a large proportion of the water would center around the 30° belts, because the thirtieth parallel divides the surface of each hemisphere into two equal parts and because the 30° belts are regions of high evaporation. Suppose we place the volume of the ice-sheets at 4,000,000 cubic miles, centered in latitude 60°. Dr. W. D. MacMillan was kind enough to calculate the resulting effect of the transfer and reported as follows:

[1] E. O. Ulrich, *Major causes of land and sea oscillations*, Jour. Wash. Acad. Sci., vol. 10 (1920), pp. 62–63.

[2] Except for certain modifying factors which need not be discussed here.

Assuming that three-fourths of the earth's surface, or 192,000,000 square miles, is water, the evaporation of 4,000,000 cubic miles of water from latitude 30° followed by its precipitation on the continents in the form of snow and ice in latitude 60° would have shortened the day by 0.36 of a second, and the water level at the equator would rise 2.41 inches. In latitude 14° (Tutuila) the rise would be 1.99 inches.

In his latest paper, Daly has given more attention to the interglacial epochs than in the earlier presentations which molded the glacial-control hypothesis. It is becoming increasingly clear that he now attributes much less to Pleistocene abrasion than to pre-glacial cutting. Thus he himself has anticipated most of the force of the objections just offered to the hypothesis of extensive marine planation under the conditions of glacial control, although to the average geologist, or biologist, the theory of glacial control still conveys the idea originally lodged, namely, that the platforms were developed by marine planation during the stages of maximum glaciation. To the present writer, however, it seems that in this shifting of the point of emphasis the glacial-control hypothesis loses one of its chief reasons for being, namely, to explain the cutting of broad platforms in spite of the protection to the shores which coral growth so steadily strives to furnish.

But perhaps it is not necessary to seek a special justification for effective wave-erosion. The protection afforded the ancient shores by coral growth is a matter of considerable speculation. To a geologist it would seem best to regard the coral growth during the interglacial periods as not very different from that existing to-day. At the present time, according to Daly, about two-thirds of the continents and larger islands in the warm tropical ocean fail to show well-developed reefs.[1] If somewhat comparable conditions obtained in interglacial times, and possibly also before the advent of the glaciers, marine abrasion in the past may well have been effective irrespective of glaciation. In any case Daly now says:

> The essential point is that the Glacial-control theory does not demand extensive benching of hard-rock islands during the Glacial period, even if its total duration were one million years. * * * The broad platforms which were essentially prepared by wave-erosion in hard rocks must date from periods long before the Glacial epoch; in these instances also the Pleistocene waves and currents did little more than smooth off any veneer of organic deposits or of detritus lying on the wave-cut flats. In brief, Pleistocene wave-abrasion merely "sand-papered" structures of which the heavy sculpturing or accretional formation had been accomplished long before.[2]

He has put forth a number of ingenious arguments to show how the shifting levels of the Pleistocene have paved the way and afforded just the conditions for the development of new reefs on these platforms, when the ice-sheets melted at the close of the glacial period. In these mud-control plays a prominent part.

Tutuila requires the cutting and building of a broad shelf around the island. Because of the relative brevity of the low-level stages of cutting during maximum glaciation, compared with the much longer period of cutting at higher levels, even within the Pleistocene itself, in addition to post-glacial time and whatever portion of pre-glacial time Tutuila may have been in existence, it seems safe to maintain

[1] Reginald A. Daly, *The coral-reef zone during and after the glacial period*, Amer. Jour. Sci., vol. XLVIII (1919), p. 141.
[2] *Op. cit.*, pp. 150–151.

that the shelf was not formed primarily under the conditions of glacial control. This conclusion is therefore in accord with the position taken by Daly in his latest paper. But the present writer does not feel the necessity for following Daly in the belief that the abrasion was done mostly in pre-glacial time. The time when the cutting was done may well be left for further evidence.

In its present form, the glacial-control theory has narrowed its scope and now centers chiefly upon a consideration of the effects of ocean chilling, changing sea-level, and consequent varying muddiness upon coral growth during the Pleistocene and early Recent time. To these inheritances many of the characteristics of the reefs to-day are attributed. It is an ingenious argument to show that in pre-glacial time the outer portions of the island shelves were too deeply submerged for the development of reefs, while the shallower portions nearer shore, being subject to frequent stirring-up of the bottom sediment in times of storm, were also inhospitable to reef corals; whereas on the other hand, in consequence of the special happenings during the glacial epochs and the rise of sea-level with the melting of the ice-sheets, new conditions developed which have been unusually favorable for the growth of reef-building corals. Daly states that these principles "operate in favor of the view that the present epoch is witnessing a quite extraordinary profusion and prosperity of reefs, whether fringing, barrier, or atoll."[1]

In view of the above discussion on the apportionment of Pleistocene time the advantage of the present over the interglacial epochs seems forced. Also, quite independently of any glaciation, the present writer believes that it would not be easy to maintain that when the plain of abrasion and outward building on the island margin had reached a notable breadth, and had become submerged to an appropriate depth, conditions away from the immediate shores would be so unfavorable for the growth of corals that a reef would not form on the outer portion of the shelf. Temperature, depth of water, and food-supply would seem to be favorable enough. The objection offered is that sediment would smother the growing corals, but one might point to the present fringing reefs, where corals to-day are growing vigorously in shallow water close to the base of the high sea-cliffs. At any rate, if the above-mentioned conditions of habitat would not permit the growth of coral with sufficient vigor to develop a reef, one may well wonder how coral reefs could ever develop at all. Yet from Silurian times on, geologic history tells us that coral reefs have been an extremely prevalent feature. They have formed around islands in the tropical seas in great abundance from early Tertiary to the present. Vaughan is authority for the statement that the Middle Oligocene witnessed the greatest known development of American coral reefs.[2] They have had their ups and downs ever since.

The repeated shifting of sea-level in consequence of the growth and waning of ice-sheets during the Pleistocene was very real and must have influenced the growth of coral reefs. The new reefs starting with the retreat of the Wisconsin glaciers, or older reefs surviving, doubtless retain many inheritances from that time of stress and shifting strands. It is easy to agree with Daly that whatever

[1] *Op. cit.*, p. 148. [2] T. W. Vaughan, U. S. Nat. Mus. Bull. No. 103 (1919), p. 226.

reefs sprang into being with the close of the Wisconsin glacial stage, since they have a comparable age, should manifest less diversity in breadth and other characteristics than otherwise would be expected. Glacial control should thus play its part in contributing to various characteristics of the present reefs. But that it has been a vital factor in the evolution of the reefs is less easy to grant.

The present writer can not accept the suggestion that there has been "stability for most of the tropical-sea floor since at least the late Miocene."[1] Under any theory of terrestrial dynamics, many changes of sea-level must have occurred in the tropical seas, as elsewhere, during this long period of more than average crustal instability. Tangible evidence is found in the embayed coast-lines and drowned valleys on many Pacific islands, as emphasized so strongly by Dana and Davis, and, on the other hand, by the elevated coral reefs on not a few of the islands. The evidence seems to show that movements of the islands, both up and down, have been intermittently in progress in the central Pacific during the span of geologic time which is recorded there. Some of these could well serve the important function of raising the sea-level which is assigned to glacial control. The subsidence of Tutuila since the formation of the shelf has, in itself, produced the desired rise of the sea upon its shores. The formation of the marginal shelf, however, indicates that Tutuila was once free from movements of the major sort, at least, for a considerable length of time.

PLANATION PLUS SUBSIDENCE.

Perhaps the chief objection which the advocates of the hypothesis of pure subsidence will offer against the explanation by combined planation and subsidence, which is here given for Tutuila, will be the inability of the waves to form the broad marginal shelf during the length of time available for its construction. It may be urged that the platform would be widened slowly and that the strand-line on Tutuila would not remain at the same level sufficiently long to accomplish the necessary cutting. Davis has objected strongly to that phase of the glacial-control theory which has called for still standing islands during the period of shelf-cutting.[2] It is certainly true that they are not still standing, but the question promptly becomes one of degree rather than of kind, and in the absence of the necessary quantitative data becomes one of opinion in which views may perhaps differ. But the present study is an attempt to explain the case of Tutuila rather than to discuss the coral-reef problem in general.

As to the rate of marine planation, Tutuila seems to testify to its rapidity. The prominent sea-cliffs on nearly all the headlands are a striking feature. Furthermore, over certain limited strips of the coast, i. e., just east of Aoloau Bay and in the vicinity of Point Nelson, not only are the headlands strongly clift, but some of the smaller valley-bottoms as well. The streams tumble over the sea-cliffs in waterfalls, some of them 40 or 50 feet in height. The streams are now out of adjustment to the sea, because their activity has not kept pace with

[1] R. A. Daly, *The coral-reef zone during and after the glacial period*, concluding sentence.
[2] W. M. Davis, *Coral reefs and submarine banks*, Jour. Geol., vol. XXVI (1918), pp. 212–217; 391–398.

that of the sea. No doubt more resistant lava layers above have retarded stream erosion while the sea was cutting weaker material below. But even so, the very existence of these hanging valleys makes the sea-cutting look impressive. A quotation from Davis is very much to the point in this connection. He says:

> There can be no question that the waves of the tradewind sea are much more powerful agents of island sculpture than the streams of short valleys and the weather changes on the valley sides.[1]

Even the very recent lava-flows which have resulted in the iron-bound coast between Nuuuli and Sail Rock have been cut back scores and probably hundreds of feet, as evidenced by outlying rocks and islets which have survived this recent and rapid cutting. The northeast coast of the island of Hawaii, between Hilo and Laupahoehoe, is a rugged sea-cliff, rising 200 or more feet above tide. Yet the flows of Mauna Kea which have built this portion of the island have been cut into only here and there by youthful streams. Volcanic islands appear to yield rapidly to wave-attack. But the basis for the belief in the wave-cut and wave-built marginal shelf around Tutuila lies not in any theoretical deductions from the efficacy of marine planation, but, as already brought out, from the field evidence of the outlying islets, particularly the Cockscomb intrusive.

Whether Tutuila could have stood still long enough for the formation of the platform is a question which can not be very profitably discussed here, for if one accepts the testimony of the Cockscomb, he will be inclined to believe that it not only could have, but must have, remained free from great shiftings of level; while if he does not consider it probable, that must remain a matter of personal opinion. Moderate changes of sea-level would not seem to the writer to preclude the cutting of such a shelf, especially as we do not know the contours of its surface, and as subaerial denudation would also play its part. On the other hand, to claim that Tutuila must have undergone sufficient movement to render the development of the shelf impossible seems unwarranted. That would practically amount to expressing doubt as to the existence of marine abrasion plains in general.

In conclusion, these investigations would seem to indicate that, so far as Tutuila is concerned, the theory of subsidence alone gives only part of the story, for much of the reef, instead of having been built up from the sloping sides of a strongly subsiding volcanic island, has developed on an antecedent bench of erosion and deposition, less deeply submerged. But subsidence, the cornerstone of the Darwinian hypothesis, has played a very important part in the upgrowth of the barrier reef and its final drowning. The interpretation here offered is more supplementary than antagonistic to Darwin's views. On the other hand, Tutuila has experienced all the vicissitudes of the composite glacial period, and they must have written their story upon it and the encircling reefs. Just how much they did is difficult to read and evaluate. It may have been a very minor part, or they may have played a far more important rôle. Much depends upon the age of the island, whose time-scale is hard to measure with any certainty. But with the

[1] *Idem*, p. 294.

seeming competency of other processes to give the observed results, it does not seem necessary, in order to explain Tutuila, to call upon the special conditions outlined in the glacial-control theory. Tutuila does harmonize nicely with the less restrictive view so clearly expressed by Vaughan in his studies of the Antillean region—namely, that the reefs have, for the most part, developed on antecedent wave-cut platforms wherever and whenever the conditions were favorable.[1] But subsidence must be added in the case of Tutuila.

[1] T. W. Vaughan, *Fossil corals from Central America, Cuba, and Porto Rico, with an account of the American Tertiary, Pleistocene, and Recent coral reefs*, U. S. Nat. Mus., Bull. 103 (1919), pp. 319–332.

LIST OF ILLUSTRATIONS.

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B. South shore of Tutuila viewed southwestward across Pago Pago Bay from summit of Papatele (1,065 ft.). The line of breakers locates outer margin of the growing fringing reef. Photo by A. G. Mayor.
C. Fringing coral reef off Cocoanut Point. From summit of Matafao (2,141 ft.).

PLATE 2.—A. Island isolated by wave attack, 0.75 mile east of Laulii.
B. Small islands which have survived the wave attack. View toward Rocky Point from shore opposite Taputapu Island.
C. Sea-cliff and wave-cut bench on promontory east of Matuu.

PLATE 3.—A. North shore of Tutuila, looking west from Aoa Bay. Outer portion of Cockscomb in distance.
B. Sea-cliff on Point Nelson. Cockscomb in distance 2.5 miles away.
C.—The cut through the Cockscomb.

PLATE 4.—A. Pioa (1,717 ft.) from near Afono. An intrusion of resistant rock which has become a peak by circumdenudation.
B.—Head of Vatia Bay. One of the large drowned valleys.

PLATE 5.—A. Village of Aua on the delta flat of a drowned valley.
B. Delta flat of Matuu. Narrow V-shaped valley above filled portion.

PLATE 6.—A. Wave-cut bench at Moloata. Small island of volcanic rock.
B. The 10-foot bench on the breached crater walls at east end of Aunuu.
C. Tower Rock and Point Distress from Blunt's Point. Tower Rock being of the same volcanic rock as that in Point Distress, shows that the island originally extended at least this far. The hillside slope just above the top of the sea-cliff has been interpreted by some as representing approximately the original surface of the island. This slope was then projected downward to the depths to accord with the Darwinian hypothesis of subsidence. This remnant out beyond the prolongation of the slope shows the incorrectness of the idea.

PLATE 7.—A. Cockscomb ridge from promontory east of Vatia. Much foreshortened.
B. Shallow lagoon between Cocoanut Point and Point Deceit, viewed from the peak of Matafao. Line of breakers marks coral-reef on outer margin of the shoal. Recent lava-flow on right. Photograph by A. G. Mayor.

A.—Cliffed headlands of south coast. View eastward from near Nuuuli. Island of Aunuu in distance.

B.—South shore of Tutuila viewed southwestward across Pago Pago Bay from summit of Papatele (1,065 ft.). The line of breakers locates outer margin of the growing fringing reef. Photo by A. G. Mayor.

C.—Fringing coral reef off Cocoanut Point. From summit of Matafao (2,141 ft.).

A.—Island isolated by wave attack, 0.75 mile east of Laulii.
B.—Small islands which have survived the wave attack. View toward Rocky Point from shore opposite Taputapu Island.
C.—Sea-cliff and wave-cut bench on promontory east of Matuu.

A.—North shore of Tutuila, looking west from Aoa Bay. Outer portion of Cockscomb in distance.
B.—Sea-cliff on Point Nelson. Cockscomb in distance 2.5 miles away.
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A CRITICAL AND EXPERIMENTAL STUDY OF DREW'S BACTERIAL HYPOTHESIS ON $CaCO_3$ PRECIPITATION IN THE SEA.

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Geologists have long been concerned with the question of the origin of lime deposits and the mechanism of $CaCO_3$ precipitation in nature. While the origin of crystalline deposits of $CaCO_3$, such as occur in calcite and aragonite, admits of a ready explanation in the conception of the solution and crystallization under proper conditions of preexisting calcareous materials, there still remains what is apparently the difficult task of accounting for the masses of $CaCO_3$ found in nature in the form of precipitated $CaCO_3$, calcareous muds, oolitic deposits, etc. In view of the foregoing, there have not been wanting attempts at the explanation of calcareous deposits in a variety of ways. Probably the simplest, most direct, and in many ways most satisfying explanation of the cause of lime precipitation as the basis for the origin of lime deposits was advanced by Murray and Irvine in 1889, and reaffirmed by Murray and Hjort in 1912. Those investigators assumed that enough $(NH_4)_2CO_3$ is produced in sea-water from the decomposition of nitrogenous substances to react with the $CaSO_4$ there, with the resultant precipitation of $CaCO_3$ in accordance with the following reaction:

$$(NH_4)_2CO_3 + CaSO_4 \rightleftarrows CaCO_3 + (NH_4)_2SO_4$$

While this explanation is simple, it must be remembered that it is open to the objection that the assumption upon which it is based, viz, the presence in the sea-water of sufficient $(NH_4)_2CO_3$ may not find justification in fact. This point will receive further consideration below. I presume that there is no necessity at this juncture of dwelling on the simple physical-chemical concepts which underlie the foregoing precipitation reaction, and am, therefore, postponing its discussion for the latter part of this paper.

The explanation of lime precipitation in sea-water remained in the hypothetical form above given until certain investigations on the denitrifying bacteria of sea-water, and especially of tropical sea-waters, gave a new turn thereto. In 1901, Brandt[1] promulgated a hypothesis which has since become known as Brandt's hypothesis, to the effect that the scarcity of phytoplankton in tropical waters is caused by denitrification of nitrates in sea-water, resulting in a paucity in nitrogenous food substances. The activity of these denitrifying bacteria is much enhanced by the favorable temperatures of those waters. With the object of securing further information on the denitrifying flora of sea-water, Drew[2] started a series

[1] Conscil Internat. Rapp. et Proc. Verb., vol. 3, Bot. Centrb. vol. 16.

[2] Report Dept. Marine Biology, Carnegie Inst. Wash. Year Book No. 10, pp. 136–141 (1911), and No. 11, pp. 136–144 (1912).

of investigations which led to his observation that, in the media employed for the work, a precipitation of $CaCO_3$ occurs. While earlier investigators had observed the precipitation of $CaCO_3$ under similar conditions, they did not invest the phenomenon with special significance. Drew, however, saw in it an opportunity for a new hypothesis for bringing to light the cause of the precipitation of lime in sea-water, and one seemingly better supported by fact than that of Murray and his associates. An opportunity for a satisfactory test of his hypothesis on the bacterial precipitation of $CaCO_3$ in sea-water presented itself to Drew when he was invited to pursue his studies at the Tortugas laboratory of the Carnegie Institution of Washington. He had been carrying on his work at Tortugas and elsewhere in the south Atlantic for two seasons when an untimely death left his work unfinished. He had almost completed for publication a paper, describing the results of his experiments, which was later published by the late A. G. Mayor, Director of the Department of Marine Biology of the Carnegie Institution. In his papers,[1] Drew proposes the hypothesis that lime precipitation from sea-water is accomplished by a certain denitrifying organism which he named *Bacterium calcis*, and gives experimental proof of that organism's active powers, in the direction indicated, by means of the precipitates of $CaCO_3$ obtained by him in cultures of that organism in *certain media* whose nature will be discussed below. The same organism was later isolated from sea-water, shipped to them from the South Atlantic, by Kellerman and Smith,[2] but was named by them *Pseudomonas calcis*, owing to its morphological characters. This is a brief account of the events which have led to the formulation of the Drew hypothesis on lime precipitation in sea-water, and which may attempt to account for lime deposits generally. Since 1913, this hypothesis has been pretty generally accepted by geologists interested in that phase of geology.

In 1920, the writer was invited to accompany A. G. Mayor, with whom as above explained Drew had worked, on an expedition to the island of Tutuila, American Samoa, for the purpose of determining if, owing to the difference between the phytoplankton in the South Atlantic and the South Pacific, there might not be corresponding differences in the bacterial flora. It seemed to Mr. Mayor particularly important to determine if *Ps. calcis* exists in the waters of the South Pacific, if it is active there, and if it can be shown to be active enough to account for lime precipitation on a grand scale. Other questions also arose as a result of the Drew hypothesis which demanded answers. To a solution of some of these questions I have addressed myself not only during a brief stay at Samoa, but during the past year (1921), in which I have given much attention to a continuation of studies inaugurated at Pago Pago and with material brought from there. It is my purpose to give below, in brief form, the results of my studies and their bearings on the Drew hypothesis and on other hypotheses which may account for lime precipitation in sea-water. I am also attempting a critical examination of the situation resulting from the Drew hypothesis, together with a constructive proposal to explain the precipitation of $CaCO_3$ in the sea.

[1] Report Dept. Marine Biology, Carnegie Inst. Wash. Year Book No. 10, pp. 136–141 (1911), and No. 11, pp. 136–144 (1912). See also Papers from the Tortugas Laboratory, Carnegie Inst. Wash., vol. 5, pp. 9–45.

[2] Jour. Wash. Acad. Sci., vol. 4, No. 14, p. 400 (1914).

CONDITIONS UNDER WHICH DREW WORKED.

The waters in which Drew worked were those surrounding the keys of the Tortugas group, principally Loggerhead Key, and those in the vicinity of the Bahamas, including the areas of the calcareous mud-flats near the latter. Starting as he did with the conception that the denitrifying bacteria were the responsible agents of calcium-carbonate precipitation, it was only natural that he should have continued to use the media employed by Gran,[1] Feitel,[2] and others. While it is unnecessary to give a detailed description of these media, it is well to name their constituents. They were as follows:

Peptone agar, consisting of peptone, potassium, nitrate, sea-water, and agar.
Potassium-malate agar, consisting of potassium malate, disodium-hydrogen-phosphate, potassium nitrate, sea-water, and agar.
Peptone gelatine, consisting of peptone, potassium nitrate, sea-water, and gelatin.
Modified Gran medium, consisting of potassium nitrate, disodium-hydrogen-phosphate, calcium malate, and sea-water.
Calcium-succinate medium, consisting of calcium succinate, potassium nitrate, disodium-hydrogen-phosphate, and sea-water.
Calcium-acetate medium, consisting of calcium acetate, disodium-hydrogen-phosphate, potassium nitrate, and sea-water.
Peptone-calcium-acetate medium, consisting of calcium acetate, peptone, potassium nitrate, and sea-water.

The last three media named were also at times made up to contain, in addition, a small quantity of magnesium tartrate. It will be noted that, in all of these media, there are supplied substances rich in easily decomposable nitrogenous compounds, substances rich in organic acids, and especially of organic acids in combination with calcium. In such media, inoculated either with sea-water or with pure cultures of *Pseudomonas calcis* isolated from the sea-water, precipitation of calcium carbonate was noted. From a study of the results of these experiments, I became impressed with the insistent thought that there was no evidence adduced in Drew's experiments that *Pseudomonas calcis* or other bacteria were possessed of the power of precipitating calcium carbonate from sea-water as such. It seemed to me to be essential in order that such a hypothesis as Drew's could be considered tenable, that the precipitation of calcium carbonate from the sea-water itself must be proved. It seemed wise, therefore, to pursue the following plan in my investigation:

1. To study the numbers of bacteria which are found in the sea-water at Samoa, both in the vicinity of the reefs and in the waters out to sea.
2. To obtain pure cultures of all the organisms which occur in the sea-water and which will grow either in sea-water alone or in media such as those which Drew used.
3. To determine whether or not any of the isolated organisms are identical with the *Pseudomonas calcis* of Drew.
4. To test any *Pseudomonas calcis* which might be isolated, as well as other organisms in the sea-water, for their powers to precipitate calcium carbonate from a variety of media, including those which Drew used, and also pure sea-water itself.

This plan constitutes the first part of my investigations carried out at Samoa. I shall now discuss the results obtained in each of the foregoing phases of my investigation.

[1] Bergens Museums No. 10 Aarbog. [2] Wiss. Meeresunters, vol. 7 (1903).

BACTERIAL COUNTS ON SEA-WATER.

Samples of reef-water, collected near the edge of the Aua reef on June 3, 1920, were plated immediately on a medium consisting of 2 grams of peptone, 0.5 gram of potassium nitrate, 1,000 c. c. of sea-water (collected in the same place as the inoculating material), and 20 grams of agar. A count of the colonies from the reef-water on the medium described showed the presence of 250,000 to 300,000 bacteria per cubic centimeter of sea-water. Further platings were then made of both the Aua reef-water and ocean-water about 2 miles from the mouth of Pago Pago Bay. Special precautions were taken in this second plating to insure the exclusion of all contaminating organisms. The Erlenmeyer flasks, which were used for collecting the samples of water for plating were entirely covered with plugging cotton before sterilization and were sterilized for 2 or 3 hours at 140° to 150° C. in the hot-air oven. After sterilization and cooling, these flasks were taken out for the collection of water, both at the reef and out to sea, in their cotton wrappers. Just before the sample was collected the cotton wrapper was removed. All preparations were made in advance for plating, so that plating was begun within 30 to 45 minutes after the samples were collected. After 4 days the sea-water taken 2 or 3 miles from the mouth of the harbor showed 1,000 bacteria per cubic centimeter, whereas the reef-water from the reef at Aua showed this time from 60,000 to 75,000 bacteria per cubic centimeter. Four days later the counts on both sets of plates had doubled, showing about 2,000 bacteria per cubic centimeter for the water out at sea, and about 120,000 to 150,000 bacteria per cubic centimeter for the reef-water.

Platings were also made on sea-water agar consisting of sea-water containing 2 per cent of agar. The total number of colonies developing on this medium was very small. The growth was very sparse and it was difficult to make proper isolations from it. Nevertheless, there were three distinct forms of bacteria found on this medium, as follows:

1. A long, slender bacillus which stained solidly with gentian violet.
2. A *Pseudomonas* form which does not stain solidly, but shows staining very much like that characteristic of organisms with metachromatic granules.
3. A short, slender bacillus.

THE KINDS OF BACTERIA ENCOUNTERED.

On the nitrate-peptone sea-water agar on which most of the plating for counts was accomplished, one dominant form of colony always appeared. The colonies were round, large, creamy white in color, and consisted of short bacilli which tended to take on a *Pseudomonas* form. It should not be assumed, however, that while this was the chief and dominant colony appearing on the plate, it was the only organism thereon, for, as a matter of fact, there were many different forms of bacteria on these plates. This was particularly true of the plates inoculated with the reef-water, which contained a large variety of bacterial forms. Even in the ocean-water, however, which, as above indicated, gave a maximum count of 2,000 bacteria per cubic centimeter on the medium in question, there were at least 7 or 8 different forms of organisms encountered. Because of the condition of systematic bacteriology at the present time, it is impossible to make any classification

or identification of the organisms studied which will prove satisfactory. I have, therefore, not attempted to identify and name the organisms which I isolated, but the following is a description, with the laboratory number of each of the organisms which were isolated and which seemed different one from another. In other words, there is omitted from this list any mention of the duplicate organisms of any kind which were isolated and studied. These brief descriptions only give an imperfect picture of the morphological characters of the organisms as noted in a microscopic examination of stained preparations.

DESCRIPTION OF ORGANISMS ISOLATED ON CALCIUM-LACTATE-PEPTONE SEA-WATER AGAR.

No. 1. Colonies small, white, circular, raised, viscid, opaque. Short rod, rounded ends. Stains solidly with gentian violet.
No. 2. Colonies much like No. 1, but organism different. Large rods, enlarged at ends; stains irregularly.
No. 3. Very small, round colony, scarcely raised above surface. Elliptical cells staining solidly.
No. 4. Colonies medium size (2 mm. diam.), raised, circular, creamy white. Short, thick rods, rounded ends; stain solidly with gentian violet.
No. 5. Large, white, raised, viscid colony, almost gelatinous in consistency. Large rod; stains solidly with gentian violet.
No. 6. White surface colony, spreading, dry, irregular. Very small rod; stains very lightly with gentian violet.
No. 7. Spreading colony. Growth very meager and delicate, irregular outline. Micrococcus; stains solidly with gentian violet.
No. 8. Small surface colony, almost colorless. Deeply staining *Pseudomonas* form.
No. 9. Spreading colony, irregular outline, not raised. Slender, short bacillus; stains solidly with gentian violet.
No. 10. Large, circular colony (3 mm. diam.) white, markedly elevated, viscid. Perfect coccus. Stains solidly. Singly and in pairs.
No. 11. Raised, circular colony. Brilliant yellow (1 mm. diam.). Coccus form. Almost certainly *Sarcina* sp.
No. 12. Large colony, watery, transparent, circular, distinctly raised. *Pseudomonas* forms; staining solidly with gentian violet.
No. 13. Small, raised, circular, light-pink colony, moist and smooth. Short, slender rod, rounded ends.
No. 14. Very small colony, dry, not raised, irregular edge. Short, thick rod; stains solidly.
No. 15. Spreading, surface colony, yellow. Short rod; stains deeply.
No. 16. Light yellow, spreading surface colony. Diplococcus; stains deeply.
No. 17. Very small, almost colorless colony, not raised. Short rod occurring in chains; stains solidly.
No. 18. Irregular, yellow colony (1 mm. diam.), raised in center, not so at edges. Short, slender rod which stains very lightly with gentian violet.
No. 19. Very small circular, raised colony, white, viscid. Streptococcus; stains very lightly.
No. 20. Light yellow, spreading colony. Small *Pseudomonas* forms. Stains very lightly with gentian violet.

The foregoing descriptions represent those organisms which, by careful attention to morphological character, were selected as being distinct from one another, though at least 12 other species were encountered which were apparently distinct forms. These descriptions are given for the purpose of showing that a wide variety of forms was encountered and that, as shown elsewhere in this paper, the precipitation of $CaCO_3$ can not be a specific property of *Ps. calcis* only, since all of these forms in the appropriate medium have the power of precipitating $CaCO_3$, many of them to the same degree as *Ps. calcis*. In view of the impossibility of classifying these organisms, I have described them only with my laboratory numbers and have foregone the more elaborate physiological and cultural tests which might be employed for possible identification. Even these very brief descriptions probably set them apart from one another very distinctly.

IS PSEUDOMONAS CALCIS AMONG THE ORGANISMS FOUND IN THE SEA-WATER OF THE SOUTH PACIFIC?

From the foregoing description of organisms which I isolated in the waters of the South Pacific, it will be noted that one bears a close resemblance to the *Pseudomonas calcis* described by Drew. This is the organism (No. 3 on the foregoing list) which forms creamy-white colonies, varying from small to large in size,

on the nitrate-peptone-sea-water-agar plates, and it is probable that on that kind of a medium this organism finds a better chance for competing with other bacteria than it does on other media and hence shows the "dominant" character to which I have referred. It must be remembered, too, that the incubation of these plates was carried out at the room temperature of the laboratory in Samoa, which was fairly constant at about 25° to 28° C. This is very close to the optimum temperature for Drew's *Pseudomonas*. There seems very little doubt, therefore, that the organism which Drew described for the water of the South Atlantic also occurs in considerable numbers in the waters of the South Pacific.

POWER OF THE ORGANISMS ISOLATED TO PRECIPITATE CALCIUM CARBONATE UNDER DIFFERENT CONDITIONS.

As indicated above, it seemed to me to be of paramount importance to this whole investigation to determine whether or not any organisms which were possessed of powers to precipitate calcium carbonate could do so in sea-water which was not in any way reinforced to make it an artificial medium. The first test, therefore, which was carried out in this part of the investigation was to inoculate sterilized sea-water in Erlenmeyer flasks and in test-tubes with pure cultures of the organisms isolated as described above. Such inoculations were made on a number of occasions and were carried out both at Samoa and at Berkeley with the same cultures. In view of the results obtained, it seems unnecessary and undesirable to give the detailed experiments on this one phase of the subject, which has required considerable time and care. It must suffice to state that in no case was I able to note the precipitation of any calcium carbonate from the sea-water. At a certain stage of this test there seemed to me to be one or two cultures which appeared to have an extremely slight power of calcium-carbonate precipitation from pure sea-water, but even this now turns out to be doubtful, since the substance assumed to be calcium carbonate was, in fact, some other very slight sediment and not calcium carbonate. It is clear, therefore, that of all of the organisms which I have been able to isolate from sea-water, both on nitrate-peptone-sea-water agar and on sea-water agar alone, none possessed the power of precipitating calcium carbonate from filtered sea-water.

In studying the results obtained by Drew and reading his discussion of them, I find myself surprised at the total lack of evidence of an attempt on his part to test the precipitating power of his *Pseudomonas calcis* or of concomitant organisms of the sea-water for their precipitating power for calcium carbonate in pure sea-water as a medium. Of course, there is a possibility that Drew had carried out a test of this kind, but his papers gave no evidence thereof. Such a test seems to me to be of such direct and crucial importance that any conclusions on this subject must strike wide of the mark without it as a support.

In view of the results obtained with the sea-water medium alone, as just described, it was only natural to inquire if the organisms in the waters of the South Pacific would not, perhaps, differ from those isolated by Drew from the waters of the South Atlantic, so that even in properly constituted media they could not precipitate calcium carbonate, and hence there would be a possibility that the *Ps.*

calcis of Drew was indeed a unique organism. With this thought in mind, it seemed to me essential to determine if in media similar to those with which Drew worked, calcium carbonate precipitation could be effected by the organisms which I succeeded in isolating from the waters of the South Pacific. Since potassium malate and calcium succinate were not available to me, I decided to employ, instead, another salt of calcium with an organic acid, namely, calcium lactate, and also calcium acetate, which was one of the salts with which Drew worked. The media thus employed were made up as follows: 1,000 c. c. sea-water, 0.5 gram potassium nitrage, 0.25 gram disodium hydrogen phosphate, 2 grams calcium lactate, 2 grams calcium nitrate. If a solid medium was desired, 20 grams of agar were added.

The calcium acetate medium was made up similarly, except that 2 grams of calcium acetate were substituted in the foregoing formula for calcium lactate.

These media were distributed in 50-c. c. portions, in 200-c. c. Erlenmeyer flasks. The flasks were plugged with cotton as usual and sterilized in the autoclave. These were then inoculated in duplicate with each of the organisms isolated from the sea-water.

In a few hours there was clear evidence of heavy growth in all the cultures, and in 48 hours a marked glassy and brittle pellicle was formed on the surface of the solution. This pellicle broke up under the touch of a platinum needle like thin ice breaks under pressure, such as that of a human foot. Only in culture No. 11, which is almost certainly a *Sarcina* species, was the growth visibly less than in the other cultures. The latter seemed to show no differences amongst themselves. On testing the pellicle and the sediment in each culture, and the sediment was heavy, marked effervescence was obtained with weak HCl. The precipitate and pellicle were crystalline and translucent in cultures of 5 or 6 days.

It is perfectly clear from the foregoing results that in the calcium-lactate medium, every organism isolated from the sea-water possesses the power of precipitating calcium carbonate. There have been, in some of the series in which this experiment has been repeatedly tried, both at Samoa and at Berkeley, a few cultures at the latter place in which no precipitation occurred, but it has been found invariably in those cases that the organism had died on the agar slants on which it had been cultured originally and, therefore, no growth occurred. Wherever growth occurred in these cultures, it was always accompanied by calcium-carbonate precipitation. In other words, therefore, I have demonstrated that I can reproduce the results obtained by Drew on the precipitation of calcium carbonate in sea-water if the proper medium is used, namely, if to the sea-water there is added a salt of calcium with some organic acid. But, what is more important, I have demonstrated by the same results that not only a specific organism, but all the bacteria isolated by me, can precipitate $CaCO_3$ from sea-water if certain salts are added to the medium. I have chosen only one series of cultures to use as evidence, since all the other series have been similar and it will save space not to repeat the results. These observations and results lead us to some important reflections and conclusions, as follows:

My results would seem to indicate, beyond a peradventure, that the power to precipitate $CaCO_3$ from sea-water containing certain other substances is not a

specific and characteristic one of any species of bacterium, but one shared in common by all organisms of the South Pacific which I have isolated. This is a conclusion diametrically opposed to that arrived at by Drew on the basis of his studies, and it is not difficult to see from the foregoing data and discussion why Drew was led to his conclusion. Having worked principally with one organism and in a medium specially suited to $CaCO_3$ precipitation by micro-organisms, the inevitable result was obtained by Drew. When many different organisms from the sea-water are tested in Drew's media, we find that they all possess the power of precipitating $CaCO_3$, but when they are tested in sea-water alone, none of them, not even Drew's *Pseudomonas*, possesses that power. The conclusion seems irresistible, therefore, that if lime precipitation from sea-water is accomplished by bacteria under natural conditions, proof therefor is entirely wanting.

It seemed of interest next to inquire what constituents of Drew's media rendered possible the reactions by which $CaCO_3$ was precipitated. For that reason, several series of experiments were arranged like the last detailed above, but differing from it in that one or more of the constituents of the nitrate-peptone-lactate sea-water was omitted. The media were constituted as follows:

No. 1. Nitrate-sea-water: 1,000 c. c. sea-water + 0.5 gr. KNO_3.
No. 2. Peptone-sea-water: 1,000 c. c. sea-water + 1 gr. peptone (Witte's).
No. 3. Nitrate-peptone-sea-water: 1,000 c. c. sea-water + 1 gr. peptone + 0.5 gr. KNO_3.
No. 4. Calcium-lactate-sea-water: 1,000 c. c. sea-water + 2 gr. calcium lactate.
No. 5. Nitrate-lactate-sea-water: 1,000 c. c. sea-water + 0.5 gr. KNO_3 + 2 gr. calcium lactate.
No. 6. Nitrate-lactate-peptone-sea-water: 1,000 c. c. sea-water + 0.5 gr. KNO_3 + 1 gr. peptone + 2 gr. calcium lactate.

No precipitation of $CaCO_3$ occurred in the cultures made up with medium No. 1, no matter which of the organisms described above was introduced therein. Likewise, inoculations of mixed sea-water cultures gave no $CaCO_3$ precipitation in that medium. In all the other media all the organisms gave some $CaCO_3$ precipitation, the largest amount of $CaCO_3$ being obtained in medium No. 6. The other media ranked as follows: No. 5, No. 4, No. 3, and No. 2, in the order of greatest efficiency to least efficiency. The differences between media 2, 3, and 4 were, however, slight. Considerable differences were apparent in the efficiency of the different organisms to precipitate $CaCO_3$ in each medium, but the variability involved was so great that no conclusions can be drawn from the results without a special variability study with the same organisms and media.

It will be noted by a brief study of the composition of the media under consideration that No. 1 is the only medium to which no organic compounds had been added. It is also the only medium to which no Ca was added. It would seem, therefore, from the foregoing results, that either the addition of organic matter in a readily soluble form like peptone, or the addition of large amounts of calcium lactate or some similar calcium salt, or both organic matter and calcium lactate, are essential to bacterial precipitation of $CaCO_3$ in sea-water. In another paper describing the continuation of my studies on $CaCO_3$ precipitation in sea-water at the Tortugas laboratory, I shall show that even the peptone, or similar substances essential to the reaction in question may be eliminated from our problem, since the peptone contains large quantities of calcium soluble in cold water. Whether or not

soluble organic matter is essential to $CaCO_3$ precipitation in sea-water by bacteria, therefore, it seems, to judge only by the experiments described above, that calcium must be added in considerable quantity to the sea-water in order to bring about the reaction in question. This subject will receive more consideration in connection with further experimental data in the subsequent paper to which I just alluded.

EXPLANATION OF $CaCO_3$ PRECIPITATION IN THE SEA.

It is doubtless true that some precipitation of $CaCO_3$ occurs in sea-water everywhere. Some geologists have assumed that such precipitation characterizes the waters of the tropical Atlantic, but not those of the tropical Pacific. We need not discuss the methods of the mineralogist which constitute the criteria by which precipitated $CaCO_3$ is distinguished from other forms of that compound in calcareous mud and similar deposits. It will suffice to state that there is, at the very least, a reasonable doubt relative to the validity of those methods. But whether or not such methods are valid, there is no denying the fact that the well-known physical forces at work in the sea are powerful enough to effect the grinding and comminution of calcareous substances, like skeletons of the corals and calcareous algæ of tropical seas, to a point in which vast accumulations of powdered $CaCO_3$ may be produced for the building, each under proper conditions, of calcareous muds of calcareous islands, and eventually of limerock. In other words, it would be easy, disregarding all consideration of $CaCO_3$ precipitation in the chemical and biochemical sense for the moment, to account, through a proper working over of calcareous remains of animals and plants by the well-known dynamic agencies of nature, for huge deposits of calcareous materials in a variety of forms. But, assuming for the sake of argument that *precipitated* $CaCO_3$ in the narrow sense of that term does, in fact, constitute a considerable part of the $CaCO_3$ in lime deposits like the chalky muds, oolitic deposits, and other lime deposits, there is certainly little or no justification, as I have demonstrated above, for the assumption that the denitrifying bacteria are the agents of such precipitation. In the paper which I have cited above, Berkeley comes to the same conclusion, independently of the writer, but does not emphasize the applicability thereof to anything but waters of the temperate zone, allowing still, in part, for its validity in the case of tropical waters, such as those in which Drew worked. Before suggesting, partly as a restatement of others' views and partly as my own explanation, the mechanism of lime precipitation, where such occurs in sea-water, tropical or otherwise, it is well to review briefly the situation resulting from the bacterial hypothesis of Drew in a critical light.

An important point in connection with the Drew hypothesis, which seems to have been completely unknown or overlooked by Drew and the present advocates of his hypothesis, and while known to him not considered for its profound significance by Berkeley, is the fact that soil bacteriologists have repeatedly shown many soil bacteria to be capable of precipitating $CaCO_3$ in media similar to those used by Drew, except that the sea-water was replaced by distilled water. The examples that may be cited in support of this assertion are numerous, and the

researches by Hall and Miller[1] with several soil organisms will serve as well as others to typify them. All of this seems to me to indicate beyond a peradventure, when we consider it in connection with the results which I have given above, that the power to precipitate $CaCO_3$ from solutions containing *large* amounts of organic acids, and particularly such in combination with calcium, is common to at least a very large number of different kinds of bacteria, whether they occur in sea-water, fresh water, or soil; that that power is, therefore, not a specific one, and that the naming of a sea-water organism *B. calcis* or *Ps. calcis*, indicating a unique and specific physiological character for that organism, is indefensible. My results indicate that, for the precipitation of $CaCO_3$ from sea-water by bacteria, conditions are essential as regards supply of organic matter and probably of calcium in a certain form, together with large numbers of bacteria, which have never been proved to be present under natural conditions in the sea. It will be seen by studying the results of Drew, of Berkeley, and myself, that bacterial numbers in the sea are very small and therefore not indicative of much physiologic power, the amount of organic matter in sea-water is known to be small, and actual tests of sea-water culture with different bacteria, whether they be the so-called *Ps. calcis* or not, have yielded negative results. In another paper I shall show that some of the $CaCO_3$ deposits regarded by Drew as precipitations through the agency of *Ps. calcis* do not occur with the necessary conditions for bacterial action to which I have just alluded.

The foregoing considerations seem to me to prove the invalidity of the Drew hypothesis on $CaCO_3$ precipitation from sea-water by an organism of the alleged specific power of *Ps. calcis*. Conservatively speaking, we may at least say that proof brought forward in support of the Drew hypothesis when critically examined is wholly unconvincing. If, however, this is the case, and we grant the validity of the contention that precipitated $CaCO_3$, as distinguished from other forms of $CaCO_3$, is found at the sea-bottom, a question which is discussed above, how can we account for such precipitation? It seems to me that the answer to this question is quite simple. It may be considered as follows: In the first place, as Murray and Irvine have suggested, where organic matter is present, say in the form of decaying sea-weed, the decomposition of the nitrogenous portion must yield, and as I have shown in experiments to be described in a subsequent paper does yield, $(NH_4)_2CO_3$. Either by direct reaction with the $CaSO_4$, abundant in sea-water, as above indicated, or by other reactions to be discussed presently, this must result in the precipitation of $CaCO_3$. Secondly, even in the absence of decomposing sea-weed, according to a simple physical-chemical concept, the $Ca(HCO_3)_2$ in solution in the sea-water only remains there as such if the proper equilibrium conditions maintain. With a disturbance of the equilibrium, as must occur with differences in the partial pressure of CO_2 within sea-water and in the air above by changes in environmental physical conditions, there must result an overbalancing amount or piling up of the Ca^{++} ion which, in turn, must result in precipitation of $CaCO_3$. Increasing pressures with increase in the depth of sea-water must result in the expulsion of CO_2, and hence in a precipitation of $CaCO_3$. Changes in

[1] Proc. Roy. Soc. B., vol. 77 (1905).

temperature of sea-water by upwelling of cold water, or by changes in air temperature, will affect the CO_2 content of the sea-water and hence determine the amount of $CaCO_3$ which will be held in solution and that which will precipitate. The agitation of the water in connection with changing winds and air conditions will affect the system sea-water-air-carbon dioxide, and hence the degree of precipitation of $CaCO_3$. All these and other environmental conditions surrounding and within the sea, since they are all likely to occur, may determine large lime precipitation. Enough has been said to exemplify the point under discussion. But even if the necessary physical conditions should not be requisite, as they undoubtedly are at times, for the precipitation of $CaCO_3$ as explained, the absorption of CO_2 by marine plants of the microscopic order must disturb the equilibrium of the solution, a change of part of the bicarbonate to normal carbonate must ensue, and $CaCO_3$ will precipitate. In connection with this change, another phase of $CaCO_3$ precipitation in sea-water may be considered. The change in reaction of the sea-water to greater alkalinity than the normal, for example, through the abstraction of CO_2 in the manner we have already seen, or through the production of $(NH_4)_2CO_3$, as suggested by Murray and Irvine, or through any increase in base, results very quickly in the precipitation of $CaCO_3$. This is, of course, related to the change concerned in CO_2 abstraction, but, for obvious reasons, needs to be emphasized separately. No further reference is made here to the chemical factors which underlie my suggestions, since they have received detailed consideration in the work of Hildebrand.[1] Bäckström,[2] and others who have demonstrated the conditions determining the solubility of $CaCO_3$, both as regards reaction of the solution and its other chemical characters.

There are, therefore, several ways in which we can explain the precipitation of $CaCO_3$ where such occurs in the sea without introducing Drew's hypothesis or any other bacterial hypothesis into the discussion. Indeed, these ways of explaining the phenomenon in question seem adequate to account for the qualitative and quantitative differences in $CaCO_3$ as found under different conditions in sea-water in nature. While Drew and others clearly appreciated and understood some, if not all, of the reactions which I have just discussed, they seem to have underestimated their adequacy to the full explanation of the phenomenon of $CaCO_3$ precipitation in sea-water, and have introduced a bacterial hypothesis which, in my opinion, based on what appear to be sound experiments and critical discussion, given above, is purely gratuitous.

[1] Jour. Am. Chem. Soc., vol. 35, pp. 847–871 (1913). [2] Ztschr. Phys. Chemie, vol. 97, p. 179 (1920).

THE CHEMICAL COMPOSITION OF LITHOTHAMNIUM FROM VARIOUS SOURCES.

By

Charles B. Lipman and P. E. Shelley

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In connection with the studies which we made on the soil of Rose Islet and the lithothamnium rock from which it originates, as elsewhere described, it seemed of interest to make a special study of the chemical composition of specimens of *Lithothamnium* representing different species that have been little altered by weathering and obtained from different sources. We were fortunate enough to obtain 8 specimens of *Lithothamnium* from Professor W. A. Setchell, who had collected most of them on our expedition to Samoa in the summer of 1920. Three reasons presented themselves for making the chemical studies in question. They are as follows:

1. There are very few data on chemical analyses of *Lithothamnium*, and especially from the South Pacific.
2. The data which are extant are all more or less fragmentary or partial analyses.
3. Such analyses as are available are of tropical forms of *Lithothamnium*. In Mr. Setchell's collection, however, there were, besides the 7 specimens from Samoa, 1 from near Monterey, California.

Table 1.—*Description of specimens.*

Lab. No.	Herbarium No. Univ. Calif.	Specific name.	Location.
1	1,084[a]	Lithophyllum proboscideum Foslie	Monterey, Cal.
2	1,050	Porolithon craspedium f. mayorii M. A. Howe	Rose Atoll.
3	1,150	Lithophyllum kaiserii (Heydr). Heyder	Aua Reef, Tutuila.
4	1,122	Same as No. 1,150 and from same reef.	
5	1,130	Goniolithon frutescens Foslie	Nuuli Reef, Tutuila.
6	1,249	Amphiroa foliacea Lamx	Utelei Reef, Tutuila.
7	1,225	Porolithon oncodes (Heydr.) Foslie	Fagaalu Reef, Tutuila.
8	1,235	Lithothamnium kaiserii (Heydr.) Heydr	Do.

There seemed, therefore, to be abundant justification for making a careful analytical study of the *Lithothamnium* specimens at our disposal. For the reader's information, it may be stated that the data gathered by other investigators have been studied by us and the following references to them may be made here. Partial analyses of *Lithothamnium* specimens or rock derived from *Lithothamnium* were reported by Hinde,[1] Skeats,[2] and Hedley.[3] Many other analyses of coral and lime rock are, of course, available, but they have no direct pertinence here and are therefore not cited. Table 1 gives a description of the specimens analyzed. The

[1] G. H. Hinde, Quart. Jour. Geol. Soc., 1891.
[2] Ernest W. Skeats, Bull. Harvard Mus. Comp. Zool., vol. 38, 1900.
[3] C. Hedley, Atoll of Funafuti. Proc. Roy. Soc. Lond. p. 177, 1904.

results of our analyses, which were carried out by the fusion method, as described by Hillebrand in Bulletin 422 of the United States Geological Survey, with such modifications as were needed, are given in table 2.

TABLE 2.—*Analysis of Lithothamnia.*

Lab. No.	1	2	3	4	5	6	7	8
	p. ct.	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*	*p. ct.*
H_2O at 100° C.	1.04	1.10	1.22	.79	.94	1.50	1.21	1.07
Loss on ignition	41.27	45.85	48.57	47.92	47.91	49.37	46.08	48.02
SiO_2	8.38	.28	.18	.16	.22	.32	.06	.02
Fe_2O_3	.64	.....	.....	.....	.....	.64	.....	.....
Al_2O_3	.89	.....	.29	.....	.....	.....	.22	.....
P_2O_5	.30	.38	.38	.48	.46	.35	.25	.46
CaO	40.31	42.22	40.28	41.76	41.76	39.02	43.78	40.76
MgO	3.88	8.00	7.84	7.28	7.28	7.53	6.55	7.69
SO_4	.97	.81	.94	.90	.91	1.08	.87	.78
Na_2O	2.78	2.06	2.93	1.91	1.57	(a)	1.42	1.10
K_2O	.34	.25	.49	.87	.38	(a)	.45	.24
Total	100.82	100.96	102.16	102.11	101.42	99.81	100.99	100.14

[a] Not enough sample for analysis.

We may first consider the possible general significance of the analytical data to the problem of assimilation and other factors relating thereto in the case of *Lithothamnium*. In the analyses we find evidence of the selective action of a plant on the constituents of its medium. With approximately twice as much magnesium as calcium in sea-water, the *Lithothamnium* stores up in its own body from 5 to 6 times as much calcium as magnesium in the Samoan species, and from 10 to 11 times as much in the California species. On the other hand, with approximately as much potassium as magnesium in the sea-water, from 3 to 5 times as much magnesium as potassium is taken up by the *Lithothamnium*. These are interesting instances of the same kind of phenomenon which is so much better known in the case of the giant kelps. In a comparison of them, we find that two forms of marine algæ living in the same medium are so far different in the nature of their selective assimilating powers that one removes enormous amounts of calcium and magnesium from the sea-water and the other enormous amounts of potassium. While these facts are more or less fully appreciated by investigators, their significance to our theories of assimilation in plant physiology is grasped by comparatively few, and even then seen only "as in a glass darkly."

Our analytical data give us further justification for insisting that neither the composition of a medium *per se* nor the composition of the plant is an indicator of what is adequate as a medium for any given plant or for plants in general. This is a concept which is not as yet generally understood or accepted by plant physiologists, and particularly by those experimenters who attempt to apply the data and observations of plant physiology. It should not, of course, be assumed that we are unaware of the possibility of a difference in the composition of the media which are available, respectively, to the giant kelp and the *Lithothamnium*. It is clear that we have no final and unexceptionable evidence that sea-water, as such,

is the medium in either case. At the point of attachment of each of these organisms, enough of the solid substrate may go into solution in the sea-water to alter appreciably the balance, if not the composition, of the medium. This is an eventuality which, however, is more possible than probable, and we do not regard its involvement in our problem of significance to the solution of the latter. How then are we to answer the question which we have raised above? Quite clearly different marine plants exhibit widely different powers of assimilation of minerals from their media and of secreting enormous quantities of them in their bodies. As plant physiologists, we have too long shied at this important problem and evaded it to the great detriment of progress in the whole subject. It is a problem fundamental to the whole subject of plant physiology, and we must address ourselves to it. If it is too difficult for any one investigator, several should be called in to advise with one another thereon; but however that is done, we appeal for immediate and vigorous action. To be sure, we have already obtained some specific evidence on the balance of the medium as an important factor in the growth of land plants. But marine plants should now receive attention. They should be artificially cultured. Because of the relative uniformity of the medium (sea-water), they offer much better material for studies on assimilation of minerals by plants than do the land plants.

The foregoing general discussion was evoked by the peculiarities of assimilation of some marine plants of which the *Lithothamnium* forms discussed in this paper seem to be of unusual interest. We may, therefore, return to a consideration of them in more detail. By far the largest part of each of the *Lithothamnium* specimens consists of the carbonate of calcium and magnesium, the actual percentages of the combined carbonates ranging from 80.15 per cent in the Monterey, California, species, to 92.19 per cent in that of the Rose Atoll specimen. It is to be particularly remarked in this connection, however, that the range of approximately 12 per cent is somewhat misleading, since the range in all of the specimens from the South Seas, considered apart from the Monterey species, is much narrower (85.44 per cent to 92.19 per cent). In fact, for all the species given in the table, with one exception, the range is less than 4 per cent. This is in part, also, doubtless referable to small errors in analysis. Nevertheless, the striking difference in the amounts of calcium and magnesium carbonates as between the Monterey species and the other species can not be passed by without special notice, and indicates pointedly the need, among others, of comparative studies of the composition of the sea-water and of other environmental factors of the two regions.

A study of the Ca content of the several *Lithothamnium* specimens in question gives no indication that there is anything fundamentally different between the assimilating powers of the Monterey species and the other species in that respect. As regards the Mg content of the different forms, however, this is not the case. There seems to be a marked discrepancy between the absorption of magnesium, as between the *L. proboscideum* and the other forms. To be sure, it is regrettable that this tentative deduction must be drawn on the basis of the analysis of only one specimen from the Monterey region. This introduces the possibility of error, which

is unfortunate. Nevertheless, the discrepancy is so large as to indicate either a lower assimilating power for magnesium on the part of *Lithothamnium proboscideum* than of the other species, or of a different ionic equilibrium in the sea-water of the different locations. The former explanation is probably the more plausible, for reasons to which, in part, we have alluded above, but chiefly because of the well-known marked differences in the secretion of one and the same substance by different organisms in the same medium. It is not unlikely that inasmuch as magnesium plays an indispensable rôle in chlorophyll formation and activation, the differences in composition of the two groups of algæ may lead to the discovery of profound differences between them in photosynthetic activity.

The most striking point of difference between the components of the Monterey species of *Lithothamnium* and the others, however, is that of the silica content. While *Lithothamnium proboscideum* contains 8.38 per cent of SiO_2, no one of the other species exceeds 0.32 per cent, and two of the specimens show almost no silica. This is another remarkable example of selective assimilation which is difficult to explain on the basis of our meager knowledge of the physiology of marine plants. That the high silica assimilation may be in some way connected with the relatively low magnesium assimilation seems at least to be probable. There is no evidence of appreciable differences in the diatom content between the two kinds of specimens.

In other respects, analyses of the two classes of *Lithothamnium* specimens show no significant differences, with the possible exception of the data on "loss on ignition." The latter are unquestionably indicative of the smaller amount of combined carbonates in the Monterey specimen than in the others, and that, in turn, is probably connected with the lower magnesium content thereof. There is room for speculation here, however, relative to the organic-matter content of each class of specimens and the possibility that differences in that respect would, in part, or in their entirety, account for the observed differences in "loss on ignition." We are not in a position to say anything relative to the significance or insignificance of the apparently high content of alumina in the Monterey specimen, as compared to little or no alumina in the other specimens. This may be connected with real differences in the Ph values for the sea-water in the two regions in question for either portions of the year or for the whole year.

Without going into further detailed discussion of the relation of the amounts of the ions present in sea-water to the amounts assimilated by the algæ in question, it is well to call attention again to the interesting comparisons of that nature which may be made from our data. Another example may suffice to emphasize further the point which we are attempting to stress. The sea-water in the vicinity of Tutuila, Samoa, contains about 130 times as much of the SO_4 as of the PO_4 ion, yet the algæ contain less than 3 times as much sulphur as phosphorus.

GENERAL DISCUSSION.

Our analyses of a number of specimens of *Lithothamnium*, representing species of the South Pacific and one California species, bring out some points of more than passing interest. We find in them striking additional evidence that the concentration of substances in the substrate does not determine the degree of assimila-

tion of such substances by algæ. This is not only in accord with the evidence to to that effect, manifested in analyses of the kelps, but also with that in the analyses of terrestrial plants and the soil solutions in which they grow. Inasmuch as our analyses are more or less complete, it is difficult to make comparisons between them and the partial or fragmentary analyses of others. Besides, there seem to be very few analyses of any kind of *Lithothamnium* material whose identity is unquestionable. Analytical data furnished by Hedley, whose work is cited above, give the most comparable data which we have found. In general, the data for the $CaCO_3$ and $MgCO_3$ content of several of his *Lithothamnium* specimens, which is all he gives, are in accord with ours, but there is a marked difference between the two, nevertheless. With one exception, Hedley's specimens show a much higher content of $CaCO_3$ than do ours. On the other hand, the $MgCO_3$ content of his specimens is, with one exception, lower than that in any of our specimens. Hedley's maximum figure for $MgCO_3$ is below that of any of our specimens, except the one from Monterey. As regards the lithothamnium rock from Rose Atoll, our analyses are, in general, confirmed by unpublished ones of Professor Phillips, of Washington, D. C., and which were furnished to Dr. A. G. Mayor. These show that the fresh *Lithothamnium* contains 74.4 per cent $CaCO_3$ and 19.47 per cent $MgCO_3$. For a more ready comparison of these data with ours, we have arranged table 3 on the basis of our analyses, which shows only the $CaCO_3$ and $MgCO_3$ content of our specimens. Owing to the fact that all other analyses to which we have referred are only partial and usually limited to Ca and Mg carbonates, the data are probably not as free from error and hence not as true to the actual conditions as ours, which give a fairly complete picture of all the constituents in the specimens analyzed.

TABLE 3.—*Ca and Mg carbonates in Lithothamnium specimens.*

[Numbers of the specimens are the same as those in table 1.]

No.	$CaCO_3$.	$MgCO_3$.	Total carbonates.
	p. ct.	*p. ct.*	*p. ct.*
1	72.00	8.15	80.15
2	75.39	16.80	92.19
3	71.93	16.46	88.39
4	74.57	15.29	89.86
5	74.57	15.29	89.86
6	69.64	15.80	85.44
7	78.20	13.75	91.95
8	72.80	16.15	88.95

Our evidence points to the conclusion that the Mg content of *Lithothamnium* forms of the Pacific is remarkably high, and particularly as compared with that of other calcareous organisms, and that, on the other hand, the Ca content is relatively low. Other factors of outstanding importance in connection with our analyses, and especially the situation as regards silica absorption, as well as general problems of assimilation which are involved, are discussed sufficiently above.

STUDIES ON THE ORIGIN AND COMPOSITION OF THE SOIL OF ROSE ISLET.

By

Charles B. Lipman and P. E. Shelley.

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The process of attempting to trace soils back to their origins is always interesting. In nearly all cases, however, it is quite unsatisfying, because of the heterogeneity of materials, sources, and causes involved in the making of ordinary soils. In rare cases opportunities present themselves for such a study which are almost ideal. One such opportunity came to us which was particularly valuable, inasmuch as it offered a chance not only to study the origin of a soil and different stages in its making, but also to reveal the nature of soil material derived from a pure lithothamnium rock from Rose Islet.

In connection with a scientific expedition to Samoa under the leadership of A. G. Mayor, Director of the Laboratory of Marine Biology of the Carnegie Institution of Washington, Dr. Mayor had the rare opportunity of visiting Rose Islet on Rose Atoll. As Dr. Mayor has fully described the islet and the conditions which he found, nothing more need be stated in this paper with reference to the general conditions obtaining there. We are in a position, however, to give an account of the chemical composition of the material from which the soil on Rose Islet is made, owing to a careful and complete analytical study which we made of the original rock, of a partially decomposed rock, and of the soil on the surface of the latter. Not being aware of the opportunities for its study which might present themselves later, Dr. Mayor made no special effort, while at Rose Atoll, to obtain soil samples. He did, however, bring from Rose Islet a small quantity of soil which adhered to the decomposing rock from which it was formed, together with good samples of the underlying compacted rock.

Samples of the materials just described were analyzed by the fusion method as employed for silicate-rock analysis. In addition, we analyzed a series of *Lithothamnium* specimens from Samoa, and, in one case, from Monterey on the California coast. These are discussed on pages 76 to 77. A comparison of these analyses brings out some very interesting points.

Before discussing the analytical data, we may make the following brief statement relative to the materials analyzed:

The soil of Rose Islet is dark brown when dry and almost black when wet. It is a fine-textured, mellow, organic soil containing many undecomposed particles of the original lithothamnium rock. The rock immediately in contact with the soil is a very loose, porous mass, very light in weight and rapidly undergoing decomposition. Beneath the stain of the soil clinging to it, it is snow white. The rock beneath that just described is a compact, fine-textured, almost pure calcium carbonate which shows no vital structure. It is pure white, fairly soft, and decomposes readily on treatment with certain chemicals.

Table 1 gives the results of analyses of the soil from Rose Islet, of the decomposing lithothamnium rock immediately in contact therewith, and of the fresh compacted and undecomposed lithothamnium rock below the latter. We give also, in table 1, an analysis of some of the water-soluble constituents in the soil and the decomposing rock. These are expressed as parts per million of the dry soil and cover merely the chief water-soluble constituents, in addition to the total water-soluble matter.

Let us now examine the results of our analyses. Even a cursory examination of the data in table 1 reveals the fact that a profound change has been wrought in the chemical composition of the lithothamnium rock in the course of its transformation into soil. In the first place, a marked change in the physical nature of the *Lithothamnium*, as it changes progressively into the intermediate rock and then into soil, is indicated by the progressive increase in its water-holding power, even in the air-dry condition. What has really occurred in the change just discussed is that a relatively compact material, like that of the lithothamnium rock, has been transformed by chemical decomposition into a more and more bulky material of much lower specific gravity, until finally a soil material very rich in organic matter is formed which supports plant growth of a certain nature very satisfactorily. This is indicated fully in the present volume by the descriptions of Dr. Mayor, relative to the forest of *Pisonia grandis* and of other plant growth which he found on Rose Islet. The organic matter of the soil was, of course, derived from the decomposing plant roots and tops, most of it probably having been contributed by the *Pisonia* trees. Our interest in this connection is mainly concerned with the large increase of surface resulting from the accumulation of the organic matter and its effect on the hygroscopic moisture-content of the materials under discussion.

In spite of the large accumulation of organic matter which accompanies the decomposition of the lithothamnium rock, the "loss on ignition" is not greatest for the soil but for the original rock. This is clearly due to the fact that the lithothamnium rock consists largely of calcium carbonate, which, upon ignition, loses its carbon dioxide.

The situation revealed by the data for the silica-content of the three materials under study is surprising. One would expect that of all the ions present, the silica would accumulate in largest quantity in the change from rock to soil. This has not been the case, however, and there is no more silica in the soil of Rose Islet than in either the original lithothamnium rock or in the specifically lighter and modified intermediate rock.

This situation may be explained on the supposition that the aluminum silicate in the original rock undergoes decomposition through reaction with ammonia, formed from the decomposition of the soil organic-matter or of the bird droppings on the islet. Such a reaction would be followed by the leaching out of the ammonium silicate formed and, while allowing of the accumulation of alumina in the soil, would prevent accumulation of silica there.

The foregoing explanation of the situation with respect to silica would seem to be supported by the data given for alumina. In the latter case we find a very large

accumulation in the soil and in the intermediate rock. While there is 20 times as much alumina in the intermediate rock as in the original rock, there is nearly twice as much alumina in the soil as in the intermediate rock. This indicates great rapidity of accumulation of alumina, with a correspondingly rapid rate of loss of other constituents of the original rock.

In this connection it is probably not amiss to point out a consideration of possible cogency which is concerned with the method of analysis for aluminum. As is well known, the precipitation of aluminum in the course of the analytical procedure is accomplished by the addition of ammonia, to the point of alkalinity, to the acid solution of the rock from which the insoluble, dehydrated silica has been removed. Under such circumstances, solutions rich in dissolved calcium and magnesium are likely to respond to the additions of ammonia by the precipitation not only of the aluminum present, but also of large quantities of the alkaline hydrates of calcium and magnesium. Under proper conditions, this results from the changes of phase in the systems. Whether or not such was the case in the present series of analyses we are unable to say positively, since no analyses of the precipitates were made. We think it unlikely, however, that anything but the aluminum was precipitated by the ammonia, since the marked discrepancies between the aluminum contents of the three samples under discussion would seem to support that idea.

If large quantities of aluminum are to be accounted for by the possibility introduced into our discussion above, then it would seem that the solution containing the greatest amount of calcium should show the greatest amount of aluminum, but as a matter of fact the reverse is true. Nevertheless, the reader's attention is directed to this interesting possibility of error in aluminum determinations which the senior author has encountered as a real factor in the analysis of sea-water.

The iron content of the lithothamnium rock and soil seems to be a factor of no significance in our discussion. At least, there is either no iron present or very small quantities thereof. In the latter case there seems to be no change in the transformation of the rock to soil.

But in the case of phosphorus, as in that of aluminum, we find marked changes accompanying the transformation of the lithothamnium rock into soil. From a little over 0.5 per cent of P_2O_5 in the compacted underlying rock, not far below the intermediate rock there is a transition to over 14.5 per cent of P_2O_5 in the latter, and from that to nearly 21 per cent P_2O_5 in the soil. These very striking quantities of P_2O_5 in the soil place it in the class of a phosphate fertilizer, which, if other conditions were favorable, would make Rose Islet of commercial importance; but the very limited area of the islet, taken together with the shallowness of the rich phosphate layer and the difficulty of obtaining cheap transportation, rule out that possibility.

The first impulse one has in attempting to account for the phosphate accumulations is to explain their origin from the bird droppings, which must be considerable in quantity, to judge from the large numbers of birds which have been found on the islet in various expeditions, such as that of Freycinet in 1819, Wilkes in 1839, and

Carnegie Institution in 1920. Our calculations indicate, however, that the bird droppings need not be considered in connection with the problem in question.

Merely on the assumption that practically no phosphate is removed by leaching in the process of change from lithothamnium rock to soil, and this assumption is fully justified by known facts, we are able to account for the large quantities of phosphates in the soil and the intermediate rock. With the phosphorus remaining practically constant in quantity, and with the other constituents being removed rapidly by leaching, a rearrangement of the percentage quantities must result which is accompanied by high percentages of phosphates in the soil. The total amounts of phosphorus found in the soil of the *Pisonia* forest are far in excess of any known to us in other soils on which plants are growing. Even the strikingly high figures given by Shedd[1] for certain agricultural soils in Kentucky are far below those which we found in the soil under discussion in this paper.

As would be expected, the lithothamnium rock suffers marked losses in lime through leaching, and these losses must inevitably increase in extent as time progresses and more organic matter is formed above the rock. This is due to the fact that the greater the quantity of organic matter, the greater the quantity of carbon dioxide produced, and the greater the amount of solvent action which will ensue as regards particularly the $CaCO_3$ constituents of the rock. It is obvious, however, that even with a change of CaO content from 44 per cent in the original rock to 29.26 per cent in the soil, the latter still remains strongly calcareous and the measurement of its hydrogen-ion concentration with the hydrogen electrode gives a PH of 7.6. In the figures for lime, as in other cases, the gradual transition of rock to intermediate rock to soil is clearly evident.

The magnesia content of the rock and soil seems to have been affected similarly to the lime by the various weathering agencies. The effect has been more marked in the case of the magnesia than in that of the lime, but there is no difference in the direction or in the general nature of the changes.

Very little comment is necessary respecting the SO_3, Na_2O, and K_2O constituents of the three materials under consideration. The percentage of potassium has increased slightly in the soil, probably because of the well-known high power of soil materials to fix that ion. This is not so clear in the case of sodium, however, since we should expect it to leach out readily, and yet the figures in table 1 show that it has accumulated in the soil to a much greater extent than the potassium. Whether or not this is in some way connected with the high content of Na in the sea-water from which the islet soil must be receiving constantly a large amount of spray, it is impossible to state definitely, but this would seem a reasonable explanation of the facts. As regards the SO_3, the facts are in accord with what one would expect *a priori*, since the $CaSO_4$ formed in the process of rock leaching and soil formation is quite insoluble and would, therefore, be proof against removal into the leachings. Moreover, in this case, as in that of the Na_2O, the sea-water would supply through its spray a quantity of sulphates which could not be retained to any great extent

[1] O. M. Shedd, *A short test for easily soluble phosphates in soils*, Soil Science, vol. XI, No. 2, p. 111, Feb. 1921.

by the rock, but would be almost completely retained by the large surface available in the soil.

We come now to a consideration of the last, but by no means the least, interesting feature of table 1, to wit, the water-soluble constituents of the Rose Islet soil and of the "intermediate" rock in contact therewith. We see at once that of the total non-volatile water-soluble salts, there is nearly 2.5 times as much in the soil as in the "intermediate" rock. Here again the enormously greater surface available in the soil than in even the porous decomposing rock is clearly shown to possess the greater power of retaining salts. Unfortunately, only a few ions were determined in this case, since the amount of material available was too small for more extended studies. The CO_3, SO_4, and Cl ions were referred to sodium and not to other ions, a procedure which is questionable, but perhaps not objectionable from the point of view of stressing the significance of these data. Only in the case of the CO_3 ion do we find a smaller amount of salt in the soil than in the rock. There is nearly twice as much sulphate in the soil as in the rock, and more than eight times as much chloride in the first as in the second. The discrepancy in water-soluble salts between the soil and the rock is largely accounted for by the difference in NaCl content between the two.

Another feature of the data for the water-soluble constituents of Rose Islet soil deserves special consideration. It is concerned with their physiological significance in connection with the forest flora of the islet. If our analyses are to be considered as even approximately correct, the *Pisonia* tree is to be regarded as one of the most salt-tolerant plants of which we have record at present. To be sure, it grows in a medium with a large organic-matter content, and hence large internal surface, which is well known to act as a deterrent to the toxic effects of salts which the soil may contain; nevertheless, the resistance of *Pisonia* to salts is particularly noteworthy. In our peat soils of the temperate region of California, we have marked evidence of the power of much organic matter to prevent the toxic effects of large amounts of water-soluble salts, but the systems there are very different, both physically and chemically, from the calcareous organic soil of Rose Islet, and the distinction between the two should be kept in mind clearly.

GENERAL DISCUSSION AND SUMMARY.

We have thus been able to trace to its origin a soil produced on an islet patch on Rose Atoll under conditions which preclude, as they do not in nearly all other cases, the obscuring effect of many variables and many contributing factors. On Rose Islet we have clearly an example of the change, chiefly induced by leaching by rain-water, and by the weathering effects of roots and other plant débris and probably slightly by the surrounding sea-water, of the distinctly calcareous lithothamnium rock into a calcareous organic soil. It would be difficult to find a case of soil origin which could be traced so certainly and with so slight a chance for error. This is particularly noteworthy because of the difficulty, if not impossibility, of such an accomplishment in the case of ordinary soils. In addition, the chemical studies which we have made render perfectly clear the rearrangements which occur

in the ionic components of the lithothamnium rock as it changes into soil. It is to be noted that such rearrangements are significantly different from those characteristic of the transformation of continental calcareous rocks into soils. The following general conclusions may be stated categorically:

1. Lithothamnium rock on Rose Islet is decomposed through leaching effects and through the progressively increasing activity of plant roots, decaying plant débris, and decomposing bird excreta. A soil of large organic matter content and highly calcareous results supports a magnificent forest of *Pisonia grandis*. The soil thus formed is different physically and chemically from either peat soil on the one hand or a calcareous clay on the other.

2. The soil, as compared to the rock with which it is immediately in contact, and with the more compacted rock below, shows enormous increases in phosphorus and aluminum, and considerable increases in sodium and sulphur. Correspondingly large decreases occur in calcium, magnesium, and volatile matter.

3. The content of water-soluble material in the soil is very large and indicates a very high tolerance of the *Pisonia* tree to the toxic effects of sodium salts.

Many other interesting points are discussed above which do not lend themselves well to summarizing. The reader is urged to read the main part of the discussion.

TABLE 4.—*Composition of Rose Islet soil.*

	Rose Islet soil.	Intermediate product.	Lithothamnium rock.	Water-soluble constituents.		
				Rose Islet soil.		Intermediate product.
	p. ct.	*p. ct.*	*p. ct.*		*p. p. m.*	*p. p. m.*
H_2O at 100° C.	5.12	2.49	0.40	Total soluble salts.	26,000	11,600
Loss on ignition	22.84	31.09	46.22	.....	.....	.....
SiO_2	.18	.20	.16	Na_2CO_3	1,837	2,171
Al_2O_3	16.72	9.20	.46	Na_2SO_4	4,414	2,435
Fe_2O_3	.40	.48	.....	NaCl	14,391	1,755
P_2O_5	20.94	14.60	.57			
CaO	29.26	35.78	44.01			
MgO	1.75	3.34	7.46			
SO_3	1.14	.87	.61			
Na_2O	1.38	1.39	.35			
K_2O	.23	.23	.15			
Total	99.97	99.66	100.40			

BACTERIOLOGICAL STUDIES ON ROSE ISLET SOILS.

By

Charles B. Lipman and J. K. Taylor

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In another paper in this series the senior author and P. E. Shelley have shown that an interesting picture of the origin of soil from lithothamnium rocks is available in the chemical studies which we made of the soil and the calcareous rock underlying it at Rose Islet, on Rose Atoll. We emphasized there the unusual conditions obtaining which permit of reasonable conclusions respecting origin, owing to the absence of any other material than the lithothamnium rock from which the soil could have been formed. The soil formed under such isolated conditions offered besides a unique opportunity for a study of the micro-organic flora of the bacterial order which can establish themselves and function there. In order, however, to obviate error arising from contamination, we needed soil that was collected under aseptic conditions. Such soil was not available among the specimens upon which we made the chemical studies and which, as pointed out in the paper cited above, were collected and furnished to us by A. G. Mayor in 1920. An opportunity presented itself to us in 1922 to obtain just such samples as we needed for the bacteriological studies. In February 1922, Captain E. T. Pollock, U. S. Navy, then governor of American Samoa, was kind enough to offer to obtain the necessary samples as soon as an opportunity should present itself for him to make the trip to Rose Atoll from Pago Pago on Tutuila. We prepared special containers accompanied by detailed instructions for collecting the soil samples under strictly aseptic conditions. Captain Pollock succeeded in making the trip to Rose Atoll early in his sojourn in Samoa and obtained samples as requested. We wish to express our profound sense of obligation to Captain Pollock for this service, by which we were permitted this rare opportunity for soil bacteriological study. The locations from which the samples were collected on Rose Islet are as follows:

Sample No. 1A.—From the center of forest of *Pisonia grandis* on Rose Islet. Composite sample of top 6 inches.
Sample No. 1B.—From the same spot as 1A, but from the second 6 inches in depth.
Sample No. 2A.—Just outside of the *Pisonia* forest, from the first 6 inches in depth.
Sample No. 2B.—From the same spot as 2A, but from the next 6 inches in depth.
Sample No. 3A.—From among the low-growing plants of *Boerhaavia tetrandra* and *Portulaca lutea*, about 50 feet from the edge of the forest, and representing an average of the first 6 inches in depth.
Sample No. 3B.—From the same spot as 3A, but representing the second 6 inches in depth.
Sample No. 4A.—From the sand entirely free from vegetation and at least 50 feet removed from any visible plant growth. It was taken about 100 feet away from sample No. 3 and about 50 feet from the beach at low tide. It represents an average of the first 6 inches in depth.
Sample No. 4B.—From the same spot as 4A, but represents the second 6 inches in depth.

It will be seen that we had samples representing the different conditions on Rose Islet in which soil with much organic matter from the *Pisonia* forest could be compared with soil containing very little organic matter outside of the forest, and samples representing the subsoil 6 to 12 inches below the surface.

The plan of our studies comprised the determination of the numbers of organisms present in the different samples and of the variety of form which could be

noted on the plates. We studied also the nitrifying powers of the soils in question and made a search for nitrogen-fixing organisms which might be present. The results obtained in each phase of the work will be discussed separately.

THE BACTERIAL COUNTS.

The soils were plated by the usual dilution methods, using sterile tap-water blanks on synthetic agar of the following composition: 1,000 c. c. tap-water, 10 grams dextrose, 0.50 gram K_2HPO_4, 0.20 gram $MgSO_4$, 0.05 gram peptone, 20 grams agar.

The final counts were made after 7 days of incubation for the plates at 28° C. The various dilutions employed showed good agreement among themselves, in fact, much better agreement than is usually obtained in plate counts of soils. That counts of bacteria in soils are subject to large errors, for reasons which have long been known to bacteriologists, is obvious, and this situation has been rendered much more serious by results of the very recent studies of Whittles,[1] involving factors which we have not suspected hitherto. Nevertheless, the counts are of some interest in connection with our studies, because of the very widely different soil materials studied. Moreover, the bacterial counts in this case are incidental to the study of the degree of diversity of form of the organisms encountered. Table 1, therefore, furnishes the data obtained in the counts which we made:

TABLE 1.—*Numbers of organisms per gram of dry soil or rock particles.*

Sample No.	No. of colonies	Sample No.	No. of colonies.
1A	1,730 000	3A	102,000
1B	1,830,000	3B	42,000
2A	23,000	4A	14,000
2B	27,000	4B	14,000

The data given in table 1 are, it appears to us, of considerably greater interest than the usual data on bacterial counts on soil. In the first place, the clear line of demarcation which is evident between the number of organisms in the several samples is definitely referable to the amounts of organic matter present in them. Moreover, the soil and subsoil samples are in such close agreement as to place these data in a class by themselves as regards the efficacy of bacterial counts. Obviously, the synthetic agar which was used for the medium in this case was unsuited for the growth of many organisms which may have been present in the samples in question. Clearly, however, it was suitable for the development of very large numbers in some cases and only of very small numbers in other cases. It can, therefore, be said to have some slight diagnostic and specific value.

It will be noted that a very large bacterial population characterizes samples 1A and 1B, which were taken within the *Pisonia* forest, where the organic-matter content of the soil is very high. The sample next approaching 1A and 1B is that of 3A and 3B, which, however, even in the surface sample 3A, contains only about one-

[1] C. L. Whittles, *Determination of the number of bacteria in soil.* Jour. Agr. Sci., XIII, part 1, Jan. 1923.

eighteenth the number of organisms of samples 1A and 1B. This is significant again because samples 3A and 3B, as will be noted above, were taken from among the low-growing plants consisting mostly of *Boerhaavia tetrandra* and *Portulaca lutea.* These plants permitted of the accumulation of more organic matter in samples 3A and 3B than in samples 2A and 2B and 4A and 4B, both of which were taken from lithothamnium sand free from vegetation. It is very striking to note in comparing samples 1A and 2A how clearly the organic matter of the forest affects the bacterial population and how the shading of the ground by the *Pisonia* trees protects the organic matter in the sand, as indicated indirectly by the bacterial populations in question. It is also interesting to note that the organic matter in the forest influences the subsoil sample, as is indicated by as high a count in sample 1B as in 1A, but that the relatively small accumulations of organic matter in 3A have a much smaller influence on the subsoil beneath it. It is perfectly clear also from the figures for samples 4A and 4B that the bacterial population, or such part of it as will develop on synthetic agar of the kind used in these experiments, is very small where virtually no organic matter is present. The calcareous material which makes up the lithothamnium débris in samples 4A and 4B is evidently an unsuitable medium for heavy bacterial growth.

KIND OF ORGANISMS FOUND ON SYNTHETIC AGAR.

In studying the agar plates which were poured for the purpose of making the counts above described, it was very noticeable that the bacterial population of the soil samples from Rose Islet was almost exclusively limited to actinomycetes. We did not have the expert guidance in our identification work to make it possible for us to indicate the probable species to which these forms belonged. We isolated all of them, however, and particularly those which seemed distinctly different from one another in their cultural characteristics. Given below are descriptions of all the different forms which we found. The descriptions do not follow the usual lines followed by the Society of American Bacteriologists, but are clear enough to distinguish the different forms one from another. Only one or two bacterial colonies could be clearly said to be other than actinomycetes and, in addition, one species of a mold is described at the end of the list of bacteria which is herewith submitted. The numbers used in the descriptions are the laboratory numbers corresponding to our isolations.

Description of Bacteria from Rose Islet Soil and Sand Grown on Synthetic Agar.

No. 4. Very slight growth in colony closely resembling bacterial colony. Barely raised above the surface of the agar. Mycelium just visible. No pigment.

No. 6. Distinct surface growth. Very slightly raised above surface of agar. White. Colonies appear like numerous dots on the medium. Leathery consistency. No visible mycelium. No pigment.

No. 7. Heavy white surface growth particularly marked along a streak on agar. Raised above surface of medium to a marked degree but not spreading. Sharply defined and markedly glistening colonies. No evidence of mycelium. No pigment. Leathery consistency. While definitely an actinomycete, this organism produces colonies more like those of bacterial colonies than any other organism in the series.

No. 8. Growth very thin at surface. Slightly wrinkled. Almost dry. No glistening appearance and no pigment. This organism may perhaps be a bacterial form.

No. 9. White, raised colony. Dense mycelium but growth limited. Not spreading. No deep growth. No pigment.

No. 12. Very similar to No. 6, but showing definitely some white raised mycelium. Points of growth smaller.

No. 18. Growth well raised above surface of medium but not heavy. Practically like a series of points on an agar slant. No mycelium visible macroscopically. Produces deep red-brown pigment on agar and a deep blue to purple pigment in solution cultures.

No. 20. Spreading colony. Well raised above agar. Colony all covered with white mycelium. Spreading growth is ragged. The edges are feathery. Not sharply defined. Slightly yellow pigment produced.

No. 22. Apparently the only true mold in all this series. Very marked growth spreading over the whole surface of the agar slant. Surface mycelium all covered by rising hyphæ. Deep greenish-gray pigment diffusing through the medium.

No. 25. Very heavy raised surface growth. White mycelium over the whole colony. As the culture ages a blue-green pigment is developed in the mycelium and a slightly diffusible yellowish pigment is visible below the surface of the agar.

No. 26. Sparse surface growth, but definitely raised from surface and covered with dense white mycelium. Not spreading. White mycelium gradually turning to greenish-gray in older cultures. Develops on agar slant in circular masses not in continuous streak. In solution cultures produces a reddish-yellow pigment.

No. 29. Surface growth spreading but not markedly raised. Mostly covered by grayish-green mycelium. At the base of an agar slant a deep brownish-yellow pigment, slightly diffusible, is produced.

No. 34. Very heavy surface growth. On agar slants development is in discrete colonies along a streak. Fair development of mycelium. Pigment blue-green and yellow-brown. Not diffusible.

No. 37. Slow-growing colonies. Not spreading, but markedly raised growth. Deep yellow pigment. Not diffusible.

No. 39. Spreading, well-raised growth all covered with white mycelium, but not raised as much or as dense as in No. 25. There is no pigment visible. Otherwise very similar to No. 20

No. 43. Vigorous surface growth, but only slightly raised above surface of agar. No evidence of mycelium. Yellow to red-yellow pigment. Not diffusible.

No. 47. Much like No. 8, but an aerial growth is slightly developed with whitish mycelium.

No. 48. Pronounced surface growth and white mycelium changing to gray and greenish gray. Growth over all of agar slant. Possibly identical with No. 26.

No. 49. Very thin, spreading surface growth. Slightly red-brown pigment. Not diffusible. Practically no mycelium apparent.

In general comment on these brief and fragmentary descriptions in which no pretense is made at a good systematic description, it may be said that the specialist working with actinomyces forms would probably find three or four new species of actinomycetes in our list. The general characteristic of this group of organisms, which seems to be by all odds the dominant group of micro-organism of the soils in question, is the relatively small colony produced by most of the forms. The tendency toward the leathery consistency so characteristic of most actinomycetes and the limitation of pigment production to a relatively few of the total number of forms found compose the differences in the behavior of some of them in Czapek's solution from those on the synthetic agar. As regards pigment formation, it would seem to open up an interesting field for investigation with regard to the influence of the chemical constitution of the medium on the kind and amount of pigment produced. This is an investigation into which we have not yet permitted ourselves to enter in a systematic and extensive way. We hope to make further studies of the actinomycetes of the soils in question, since parts of the original samples are being carefully preserved, and if we do not succeed in such a detailed study of the actinomycete forms of the Rose Islet soils we shall hope to interest some specialist in that work.

It is an interesting question, and one which we can not presume at this juncture to answer, why this particular kind of soil material, made up largely of lithothamnium fragments and organic matter, should be suited chiefly and almost exclusively to the development of actinomycetes. The origin of these bacteria in the soil of Rose Islet must also be referable to a variety of causes. The Pacific Ocean water itself, as some of the senior author's investigations have shown, can not possibly be conceived as having contributed very many, if indeed any, of the forms described

in this section of our paper. The excrements of birds, however, which are constantly bringing materials from various parts of the Pacific to Rose Islet, might well have introduced most of the forms now found there. The boobies are reported to be very numerous at Rose Islet and have unquestionably contributed much to the surface organic matter in the *Pisonia* forest, where they nest. With that organic matter would unquestionably come the bacterial forms under discussion.

As a final comment on the organisms developing on synthetic agar, it may be said that there were in all about 26 types of colonies which we could distinguish as being distinct from one another. Of these 26 types it seems certain that 20 were actinomycetes, a possible 5 were bacterial forms, and one was a mold. On mannite agar instead of synthetic agar two actinomyces forms were obtained which were not noted on the other medium.

THE NITRIFYING BACTERIA OF THE ROSE ISLET SOILS.

It is, of course, well known that the nitrifying bacteria do not develop colonies on ordinary synthetic media or on any other media containing much soluble organic matter. In experiments described by the senior author[1] elsewhere, it has been shown that nitrifying bacteria do not exist or can not develop in sea-water, even though they may be present in active condition in coral sand which is in constant contact. with sea-water. Any nitrifying bacteria which would be found in the Rose Islet soils would, therefore, probably take their origin in coral detritus which probably underlies the *Lithothamnium* masses which now rise above the Pacific and compose the material of Rose Islet on Rose Atoll, or are contributed by winds and birds in a variety of ways to the original sandy surface of Rose Atoll. However that may be, we have made a study of the nitrifying bacteria which exist in the samples of soil from Rose Islet under discussion in this paper.

The results of our investigations show that both the nitrite and nitrate producing bacteria are present in all the soils. The speed with which they encompass the task of nitrification, however, is quite a variable one in the different samples of soil. Moreover, the nitrate organism is much more active than the nitrite organism in these soils. The most active nitrifying bacteria are in soils 1A and 1B, and the weakest nitrifiers are in soils 4A and 4B. It is, therefore, apparent that the total organic matter in a soil, just as in the case of agricultural soils, so far from limiting the activities of the nitrifying bacteria, actually appears to be beneficial to their growth and nitrifying powers. This seems perfectly intelligible when we reflect that with the small bacterial population which we have shown to be characteristic of samples 4A and 4B and 2A and 2B, which in turn is referable to the limited quantity of organic matter there, there would necessarily be a deficient supply of carbon dioxide. Since carbon dioxide is used for the synthesis of organic matter by the nitrifying bacteria in much the same ways as it is used by green plants, it follows that the soils with the largest amount of organic matter and the best bacterial flora of other kinds should also be the soils with the best nitrifying power. This *a priori* reasoning seems to be borne out by the experimental results obtained on the nitrifying bacteria of the Rose Islet soils.

[1] Charles B. Lipman, *Does nitrification occur in sea-water?* Science n. s., vol. LVI, No. 1453, p. 501, Nov. 3, 1922.

In further experiments with the nitrifying bacteria from these soils, we attempted the invigoration of some strains of both the nitrite and nitrate formers. This invigoration was brought about by the constant supply to a given culture of more and more nitrifiable material after it had once begun the oxidizing activity. The nitrifying organisms from soil 1B, which is the subsoil from the *Pisonia* forest, seem to be the most efficient of the cultures which we studied. One such culture oxidized 14 mg. of nitrogen in ammonium sulphate completely to nitrous acid in 7 days, and the corresponding nitrate organism from the same culture oxidized 30 mg. of nitrogen in sodium nitrite completely to nitrate in 3 to 4 days. This gives some idea of the general activity of the nitrifying organisms in this soil and gives the basis for the statement made above to the effect that the process of oxidation of nitrite proceeds, at least in these cultures, at a more rapid rate than the oxidation of ammonia.

In view of these results, we arranged another experiment in which we started with the usual solutions employed in nitrification work (something like those employed by Omeliansky). By making up solutions like these for both the ammonium sulphate and the sodium nitrite series and distributing them in Erlenmeyer flasks in 50-c. c. portions and then inoculating with 1 gram of soil from each of the samples studied, we were enabled to determine the period necessary for the complete oxidation of ammonia to nitrous acid and of nitrites to nitrates. In the solutions used there were present in each of the ammonium sulphate cultures 11 mg. of nitrogen, and in the sodium-nitrite cultures, 33 mg. of nitrogen. Table 2 gives the number of days necessary for the complete oxidation of ammonia and of nitrite by organisms in each of the soil samples.

TABLE 2.—*Rate of oxidation of ammonia and nitrate nitrogen by Rose Islet soils.*

No. of soil.	Nitrogen compound.	No. of days.	No. of soil.	Nitrogen compound.	No. of days.
1A	Sodium nitrite	18	3A	Sodium nitrite	22
	Ammonium sulphate	27		Ammonium sulphate	33
1B	Sodium nitrite	18	3B	Sodium nitrite	28
	Ammonium sulphate	27		Ammonium sulphate	38
2A	Sodium nitrite	24	4A	Sodium nitrite	38
	Ammonium sulphate	33		Ammonium sulphate	(a)
2B	Sodium nitrite	20	4B	Sodium nitrite	(a)
	Ammonium sulphate	33		Ammonium sulphate	(a)

[a] Not complete in 38 days.

The fact that nitrifying bacteria are found, even if in small numbers, in all the soils of Rose Islet, whether they be bare sands with little organic matter in them or soils very rich in organic matter as is that of the *Pisonia* forest, would seem to indicate the correctness of an observation that has many times been made by the senior author to the effect that the nitrifying bacteria are probably the one group of all the numerous forms of bacteria known which are universally distributed over all the earth's surface. We know of no case of a soil at the present time in which no nitrifying bacteria have been found. It would be interesting to speculate on the

significance of this universal distribution of the nitrifying bacteria, both as regards their unique chemical powers, which seem to be limited to them alone of all micro-organisms, and as regards the antiquity of their origin. A more intensive study of this question on just such material as that of Rose Islet would be certain to return highly interesting and valuable results.

A SEARCH FOR AZOTOBACTER IN ROSE ISLET SOILS.

When inoculated into mannite agar of the type used in nitrogen fixation and *Azotobacter* work, the Rose Islet soils cause visible fermentation in the medium and produce a very thin pellicle or membrane at the surface of the solution which at first sight might seem to be an *Azotobacter* membrane. As a matter of fact, however, the membrane is not characteristic of the *Azotobacter* forms. It is too thin for the luxuriant development of the *Azotobacter* cells which are characteristic of cultures containing a vigorous flora of *Azotobacter*. An examination of this membrane shows many rods and then and when coccus and diplococcus forms of what might be *Azotobacter chroococcum*. These cells are isolated, however, and are clearly in too small a number and living under conditions of competition apparently unsatisfactory to their vigorous development. It may even be questionable if these few cells noted as *Azotobacter* in some of the cultures of the Rose Islet soils are truly *Azotobacter* cells. They resemble them very closely; nothing more positive may be said about them at the present time. In cultures from soils 4A and 4B there was not even a membrane produced. The closest approximation to the appearance of *Azotobacter* cells was in culture 3A. In general, it would seem that *Azotobacter* cells do exist in some of the soils, and particularly in 3A, but that they do not find conditions propitious for their rapid development in competition with the other forms which occur there.

GENERAL REMARKS.

A number of circumstances conspired to prevent us from making a search for other groups of micro-organisms by the use of specialized media with the Rose Islet soils. It is possible that the future may bring an opportunity to carry on such further investigations, since, as above stated, parts of the samples are still available. Among these further studies there should certainly be an investigation of cellulose-dissolving organisms and of the cultural characteristics of the actinomyces forms.